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2015

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Impacto de Mobilidade em Encaminhamento centrado no Utilizador

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Tese apresentada às Universidades de Minho, Aveiro e Porto para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Eletrotécnica / Telecomunicações no âmbito do programa doutoral MAP-Tele, realizada sob a orientação científica da Doutora Rute C. Sofia, Professora Associada da Universidade Lusófona e Directora da Unidade de Investigação COPELABS – Associação para a Investigação e Desenvolvimento em Cognição e Computação Centrada nas Pessoas e da Doutora Susana Sargento, Professora Associada do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro.

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palavras-chave

Encaminhamento por múltiplos saltos, métricas baseadas em mobilidade, redes sem fios, rede centrada no utilizador

resumo

Os paradigmas recentes de arquiteturas de comunicação sem fios consistem em ambientes onde os dispositivos apresentam um comportamento dinâmico (e.g., Redes Centradas no Utilizador). Nestes ambientes, o encaminhamento de dados ainda é realizado com base no comportamento de armazenamento e encaminhamento da comutação clássica de pacotes. Embora seja suficiente para calcular, pelo menos, um caminho adequado entre uma origem e um destino, tal comportamento de encaminhamento não é adequado nas redes móveis e sem fios atuais.

Esta tese tem como objetivo analisar o impacto da mobilidade dos utilizadores sobre os diferentes cenários de encaminhamento. A tese também visa o desenvolvimento de conceitos de encaminhamento que ajudam na distribuição de dados através de grafos, nos quais os vértices exibem padrões de mobilidade humana, como é o caso hoje em dia para a maior parte das redes sem fios centradas no utilizador. A primeira parte desta tese envolveu a análise do impacto da mobilidade dos utilizadores no encaminhamento, com a análise de que a mobilidade, para afetar o desempenho do encaminhamento, depende do comprimento do caminho entre a origem e o destino, da distância entre os dispositivos, e dos diferentes padrões de mobilidade. O estudo dos atuais parâmetros de mobilidade mostrou que eles capturam parcialmente a mobilidade dos utilizadores. A robustez dos protocolos de encaminhamento depende da sensibilidade das métricas no que concerne a esta mobilidade. Assim, foram concebidas métricas de encaminhamento baseadas na mobilidade dos utilizadores para aumentar a robustez do encaminhamento em relação à mobilidade. As duas categorias de métricas de encaminhamento criadas foram métricas que têm como base o tempo e a correlação espacial.

Para a validação das métricas foram utilizados vários modelos de mobilidade, incluindo os modelos que imitam padrões de mobilidade humana. As métricas foram implementadas utilizando a ferramenta *Network Simulator* e considerando dois protocolos de encaminhamento por múltiplos saltos amplamente utilizados, o *Optimized Link State Routing* (OLSR) e o *Adhoc On Demand Distance Vector* (AODV). Com a utilização das métricas propostas observa-se que a frequência de realização de novos cálculos de caminhos de comunicação foi reduzida em relação à métrica de referência. Isto significa que foram usados caminhos mais estáveis para encaminhar dados. As métricas de encaminhamento baseadas no tempo apresentam geralmente um bom desempenho nos diferentes cenários de mobilidade utilizados. Observou-se também uma variação no desempenho das métricas, incluindo a métrica de referência, nos diferentes modelos de mobilidade considerados, devido a diferenças nas regras de mobilidade dos utilizadores dos diferentes modelos.

keywords

Multihop routing, mobility aware metrics, wireless networks user-centric networking.

abstract

Recent paradigms in wireless communication architectures describe environments where nodes present a highly dynamic behavior (e.g., User Centric Networks). In such environments, routing is still performed based on the regular packet-switched behavior of store-and-forward. Albeit sufficient to compute at least an adequate path between a source and a destination, such routing behavior cannot adequately sustain the highly nomadic lifestyle that Internet users are today experiencing.

This thesis aims to analyse the impact of the nodes' mobility on routing scenarios. It also aims at the development of forwarding concepts that help in message forwarding across graphs where nodes exhibit human mobility patterns, as is the case of most of the user-centric wireless networks today. The first part of the work involved the analysis of the mobility impact on routing, and we found that node mobility significance can affect routing performance, and it depends on the link length, distance, and mobility patterns of nodes. The study of current mobility parameters showed that they capture mobility partially. The routing protocol robustness to node mobility depends on the routing metric sensitivity to node mobility. As such, mobility-aware routing metrics were devised to increase routing robustness to node mobility. Two categories of routing metrics proposed are the time-based and spatial correlation-based.

For the validation of the metrics, several mobility models were used, which include the ones that mimic human mobility patterns. The metrics were implemented using the Network Simulator tool using two widely used multi-hop routing protocols of Optimized Link State Routing (OLSR) and Ad hoc On Demand Distance Vector (AODV). Using the proposed metrics, we reduced the path re-computation frequency compared to the benchmark metric. This means that more stable nodes were used to route data. The time-based routing metrics generally performed well across the different node mobility scenarios used. We also noted a variation on the performance of the metrics, including the benchmark metric, under different mobility models, due to the differences in the node mobility governing rules of the models.

Contents

List of Figures

List of Tables

List of Acronyms

ALB Average Number of Link Breaks

AODV Ad hoc On-Demand Distance Vector

AP Access Point

CMM Community Mobility Model

CRAHN Cognitive Radio Ad-hoc Network

CRAWDAD Community Resource for Archiving Wireless Data At Dartmouth

DSDV Destination-Sequenced Distance-Vector

DSR Dynamic Source Routing

DTN Delay Tolerant Network

DV Distance Vector

GPS Global Positioning System

IETF Internet Engineering Task Force

IP Internet Protocol

LD Link Duration

LET Link Expiry Time

LF Link Lifetime

LS Link State

LSA Link State Advertisement

MAC Media Access Control

MANET Mobile Ad Hoc Network

MAODV Mobility Prediction Ad hoc On demand Distance Vector

MP Mobility Prediction

MPR Multipoint Relay

NS2 Network Simulator 2

OLSR Optimized Link State Routing Protocol

ORBIT Open-Access Research Testbed for Next-Generation Wireless Networks

OSI Open Systems Interconnection

QoS Quality of Service

RERR Route Error

RPGM Reference Point Group Mobility

RREP Route Reply

RREQ Route Request

RWP Random WayPoint

SLAW Self-Similar Least-Action Human Walk

SNR Signal to Noise Ratio

TC Topological Control

UCN User Centric Network

VANET Vehicular Ad Hoc Network

List of Definitions

Forwarding	The process of transmitting information from a source node to another node, towards a destination.
Heuristic	Exploratory problem-solving approach that follows a practical method to speed up the development of sufficiently robust solutions.
Hop	Considered in the context of packet-based networking, a metric value used to measure distance based on the number of network nodes a packet traverses. Each time a device forwards a packet onto a segment this counts as a single hop. Routing protocols that observe hops as their primary metric value consider the best or preferred path to a destination (when multiple paths exist) to be the one with the least number of network hops.
Link	The radio association between two nodes that are within the transmission range of each other.
Link Duration	Parameter corresponding to the period of time when two nodes are within the communication range of each other.
Link Length	The physical distance between two nodes with a valid link.
Metric	A quantitative value, calculated by an algorithm, used to evaluate a cost for selecting or rejecting a specific goal.
Routing Metric	A metric to be applied to a routing algorithm, applied to assist in selecting a close-to-optimal path for a specific destination.
Mobility cost	A routing cost associated to a node or to an association between two nodes, derived from a metric that is sensitive to movement of the nodes.
Multi-hop routing	Routing involving multiple hops to a destination.

Neighbor	A node with which the current node has an association with (a link).
Network	A group of two or more computing devices connected via a form of communications technology.
Network lifetime	Period of time that elapsed from the time a topology becomes active to the time when it becomes disconnected, from a destination reachability perspective.
Node	A portable device with wireless capability via one or more interfaces, often carried by humans.
Node degree	Number of neighbors of a node.
Node mobility	Movement of a node.
Node mobility pattern	Pattern of movement of a node .
Node lifetime	Period of time since a node becomes active until the node is said to be dead, i.e., from a network perspective, the node ceases to exist.
Number of link breaks	Number of links that cease to be valid due to mobility.
Number of New Neighbors	Number of links that have been formed within a sampling interval.
Path	Defined as a path that minimizes (or maximizes, respectively) the rank value between any given pair of source-destination nodes, as well as its sub-paths.
Path Weight	A value representing link or/and node characteristics of a path. This definition coincides with "path cost" defined in RFC6719.
Pause Time	Interval of time during which a node has zero speed or close to zero [17].
Routing	The process of computing a cost for a node to find a path towards a destination node.
Spatial Correlation	Correlation, in time and space, that a node has with a specific set of neighbors.
Stationary time	Refer to Pause Time.
Wi-Fi	Wireless Fidelity.

Chapter 1

Introduction

The most recent paradigms in wireless communication architectures describe environments where nodes present a dynamic behavior, e.g. *Mobile Ad-hoc Networks, (MANETs)* or *User Centric Networks, (UCNs),* where nodes are in their majority end-user devices with human mobility characteristics [1]. In such environments, routing is still performed based upon the regular packet-switched behavior of *carry-and-forward*. Specifically, nodes keep forwarding state about the possible location (or direction) of destinations and compute paths based on such information. In addition, the most popular routing protocols in such environments rely on the paradigm of single-source shortest-path computation.

Albeit sufficient to compute at least an adequate path between a source and a destination, such routing behavior does not adequately sustain the highly nomadic lifestyle that Internet users are experiencing today. In contrast to traditional Internet routing scenarios (be it based on wireless or wireline technologies), UCNs face new forwarding and routing challenges, due to their underlying assumptions, namely: i) end-user device nodes may behave as networking nodes; ii) nodes have a highly nomadic behavior as they mimic human mobility behavior; iii) data is exchanged based on individual user interests and expectations; and iv) control and management requires decentralized and distributed solutions [1]. The highly nomadic behavior achieved in such environments has an additional intrinsic property, which is the fact that wireless devices are, in their majority, carried by human beings. This means that their movement follows human mobility patterns [74]. Human mobility patterns are characterized by frequent movements that can be predictable, and that can also have preferred locations where humans spend some time with some periodicity [29][74][41]. Movement of the devices impacts the wireless signal, connectivity models, as well as the routing performance. In addition, movement of the devices changes with space and time, i.e., it shows a *spatial-temporal* correlation. Ideally, if one can integrate some of such mobility characteristics based upon human behavior to routing in dynamic wireless networks, then routing becomes more robust and with better performance. Therefore, mobility modeling and its impact on routing are highly relevant not only for UCNs, but for wireless scenarios in general.

The main goal of this thesis is to analyse the impact of node mobility in multi-hop routing, study the existing mobility metrics and their capability in incorporating mobility aspects, as well as devise better mechanisms to make routing more robust to node mobility. Our expectations are to provide current multi-hop routing mechanisms with metrics that make them more flexible to node movement, having as consequence an optimized network operation, reducing the need to recompute paths in the presence of node movement.

The thesis starts, in section 1.1, with an overview of the steps taken to reach the proposed goals. Section 1.2 describes the roadmap, while section 1.3 covers the methodology. The chapter is concluded in section 1.4 with a summary of the main contributions of this work.

In addition to the introduction, this thesis is split into five chapters, organized as follows:

Chapter 2 debates wireless architecture evolution, multi-hop routing and the impact of node mobility on routing. Due to node mobility, routing performance is affected by the increased frequency and volume of link breaks. In UCN environments where end-user devices act as networking nodes, node movement patterns partially mimic human roaming patterns. The chapter, reviews work that aims at understanding the impact of node mobility on routing and mobility parameters used to measure node mobility. The chapter further provides a review on human mobility patterns, since user-centric environments have nodes bearing human mobility characteristics. *Quality of Service (QoS)* and energy aspects are also reviewed in the chapter as they are related to node mobility.

Chapter 3 discusses routing metrics that have been developed to increase multi-hop routing protocol sensitivity to node mobility. The chapter starts with an overview concerning examples showing the impact of mobility on path re-computation. Then, it covers the main parameters that are today available and that can be considered to develop routing metrics that make routing more sensitive to mobility. The chapter then discusses our proposed metrics, which are categorized into two main branches: metrics that are time-based, and metrics that are based on time and space correlation from a node towards neighbors, named spatial-correlation metrics.

Chapter 4 provides information on the integration of the proposed metrics into current protocols, having *Optimized Link State Routing Protocol (OLSR)* and *Ad-Hoc on Demand Routing Protocol (AODV)* as examples. The validation of these metrics under varying conditions and for the mentioned protocols are also addressed in this chapter.

Chapter 5 concludes the thesis, highlighting its findings, addressing the related challenges, and proposing guidelines for future work in this field. Then, in Annex A a list of success indicators achieved during this work is provided.

1.1 Solution Overview

User-centric environments are characterized by nodes whose mobility patterns are similar to the ones of humans' movement, as these nodes may be portable devices carried and controlled by humans. As a consequence, topologies in user-centric environments are more prone to variability, as nodes run out of battery, and their holders move accordingly with an individual (social) routine. Given that node mobility affects routing performance due to the invalidation of routing paths (e.g. due to single or multiple link breaks), networking architectures of user-centric environments are prone to poor routing performance due to their relatively high level of mobility variability. This work analyses node movement and the impact of such movement in the routing process. We noted that the duration of a link, the distance between nodes, the node individual movement as well as the node collective movement are aspects that play a significant role in node mobility, as far as routing is concerned [14]. This analysis has been extended to assess also how these aspects affect routing phases. To capture node mobility, *mobility-aware* parameters have been applied. The level of sensitivity to track movement impact (e.g. long-term or short-term impact) can assist in leveraging existing multi-hop routing protocols in dealing better with topology changes. In a first phase of the work, our analysis of existing mobility parameters showed that they capture node mobility, but only partially [17][15]. As previously explained, UCNs are environments that are highly variable in terms of mobility patterns, as devices are partially controlled by the Internet end-user. Nevertheless, multi-hop routing approaches are applied also in these environments in their native format, and thus are not capable (as they were not designed to be) of becoming more robust to short-term topological changes due to node mobility. As such, we have proposed routing metrics integrating existing and new mobility-aware parameters. These metrics aim at making routing more robust in dynamic environments [19][16][18]. The proposed metrics have been split into two different categories, *time-based* and *spatial correlation-based*. The routing metrics were validated in two representative multi-hop routing protocols: AODV and OLSR. Even though the proposed metrics have been validated via discrete event simulations, this work comprises also a full specification to integrate our metrics into both AODV and OLSR, thus assisting the reader in easily implementing the proposed metrics in the context of these protocols, as well as to extend their usage by integrating them in new protocols.

1.2 Proposed Roadmap

The proposed work, which has been introduced in the thesis proposal [95], aims to analyse the impact of node mobility on routing and to develop novel mobility-aware routing metrics, algorithms, and if necessary, a protocol or improvements to existing protocols to improve the performance of routing in the face of mobility. The target scenarios comprise wireless networks where the majority of nodes are carried and/or controlled by humans. Thus, in these scenarios networking nodes are essentially characterized by having restricted networking resources (bandwidth, energy) and a highly nomadic behavior. To address these aspects, we have considered the following goals:

- Analysis of routing approaches that consider integration/support of mobility awareness in their architectural design.
- Devise novel algorithms and/or mechanisms that aim at making multi-hop routing more robust in dynamic environments.
- Validate and demonstrate these algorithms in the context of existing approaches.

With the objective to reach such goals, our work focused on solving the following challenges:

- What is the impact of different mobility features in current single-source shortest-path approaches?
  - Consider features such as node direction, speed, acceleration offset, and periodic location visits.
  - Analyse different performance parameters, e.g., convergence time, throughput, multipath support.

- How can routing mechanisms become more tolerant to mobility aspects that reflect regular movement patterns (e.g., ping-pong effect)?
- Is shortest-path routing truly suitable for networking environments where nodes attain a high degree of freedom in movement?
- Can other-than-shortest-path approaches (alternative routing approaches) improve the network robustness?

To achieve such goals and the roadmap according to Table 1.1, we have considered a number of activities, which are described in prior doctoral program MAP-TELE progress reports [98], [97], [96].

Concerning the roadmap, the proposed scheduling has as follows:

- Activity 1: Brainstorming phase (September – December 2009).

Expected outcome: intermediate progress report, debate on novel approaches.

- Activity 2: Specification/validation phase 1 (January 2010-October 2010).

Expected outcome: intermediate report; novel algorithms and/or mechanisms specified (main aspects) and validated (simulations).

- Activity 3: Specification/validation phase 2 (December 2010 - August 2011).

Expected outcome: intermediate progress report; novel algorithms and/or mechanisms and/or updates specified and validated (simulations or testbeds).

- Activity 4: Validation/demonstration (September 2011 - October 2011).

Expected outcome: intermediate report; novel algorithms and/or mechanisms and/or updates specified and validated (simulations or testbeds).

The schedule was later revised [96] and the final schedule was as follows:

- Link Stability Metric (August-September 2012).
  - Implementation/Performance evaluation of the link stability metrics in OLSR.
- Spatial Correlation Metric (August 2012 - October 2012).

Table 1.1: Thesis RoadMap Summary.

Year	Planned Activity.
2009	Debate of Novel approaches.
2010	Devise novel algorithms and/or mechanisms specified (main aspects) and validated (simulations).
2011	Provide an analysis based on simulations of the different proposed metrics when applied to both distance-vector and link-state approaches.
2012	Refinement of the proposed routing metrics, and evaluation of potential improvements.
2013	1)Refinement of the metric on link duration with tolerance interval. Implementation of the metric in AODV and OLSR. 2) Thesis wrap up.

  - Implementation/Performance evaluation of the Spatial correlation metrics in AODV and OLSR.

- Link Duration Tolerance Interval Metric Revisit (December 2012 - January 2013).
  - Refinement of the metric on Link duration with tolerance interval.
  - Implementation of the metric in AODV and OLSR.

- Thesis Writing and Wrap-up (February 2013 - April 2013).
  - Thesis wrap-up aspects.

Based on the proposed plan, several activities were pursued. On a first brainstorming phase (2009), we analysed related work and existing parameters. We noted that link length, mobility patterns and distance are mobility aspects that play a role in determination of whether or not node movement leads to link breaks. The outcome was a publication in a national conference [14]. On a second phase, the work delved into the impact of movement in different routing phases (i.e. path discovery and path maintenance). Since mobility parameters are used to capture node mobility, we therefore needed to know to what extent they would capture mobility. We analysed a number of them (refer to chapter 3) and observed that they did capture node mobility, but only partially. Following our analysis and still during brainstorming, the next step was to understand the environments where node movement was relevant (e.g., UCNs, community networks). As such, our analysis was extended to integrate a better understanding of human mobility modeling. Based on these studies, we started investing in routing metrics that were time-based. In parallel, the setup of the validation work was started in the context of NS2 simulations (2011 and 2012). After this period, our work led to the development of spatial correlation metrics. The outcome of the progression (2012-2013) was a journal paper, book chapter, conference papers, workshop papers and code for the metrics [15][17][16][103][18][13][19][104][103].

1.3 Methodology

The PhD work started in December 2008 in the context of MAP-TELE, being my wish to research in mobility management in wireless networks. I have opted for a theme proposed by my current scientific adviser (Dr. Rute Sofia), where the intention was to analyse up to which point we could make multi-hop routing approaches more sensitive to movement. The scientific adviser presented a hot topic that considered recent advances in wireless technology such as *Wireless Fidelity (Wi-Fi)*, giving rise to new types of portable devices and to new types of connectivity models, e.g., UCNs. The topic was appealing to me because I had a working background in cellular networks, where mobility management was something I dealt with frequently, and given that there was a new twist in the area, I looked forward to be part of the solution. Together, and based on weekly meetings, we established a roadmap, which culminated in my thesis proposal being submitted in July 2009. The proposed roadmap considered a debate on novel approaches in the area of study to be followed, by devising novel algorithms that would make multi-hop routing more robust, and the last phase would be the validation of the algorithms.

To achieve the goals proposed in this thesis, and following the roadmap, weekly meetings with the advisers have been held. An extensive literature review was conducted to be up-to-date with current mobility approaches towards multi-hop routing. It was also done an analysis of node mobility impact on multi-hop routing, followed by the review of mobility parameters that are used to capture node mobility. Having analysed the impact of node mobility on routing and having found out the inadequacies of mobility parameters, preliminary routing metrics, aimed at making routing more robust, were devised. At the same time, a review of validation options of the mobility-aware routing metrics was done, ranging from testbeds, emulators and simulations, use of human traces to mimic node mobility and synthetic mobility models. The simulations proved to be the most feasible option at the time, and the review of simulation tools were conducted, where network simulator version2 (ns2) was chosen due to its wide use, available support, and stability.

In regards to the node mobility patterns, human traces obtained from *Community Resource for Archiving Wireless Data At Dartmouth, (CRAWDAD)* [105], a community resource for archiving wireless data at Dartmouth, were used initially. However, they proved inadequate due to the high frequency of network partitions in the topologies. This would lead to find another option which required the use of traces from synthetic mobility models.

Subsequent mobility metrics that were devised were simulated in NS2 using multi-hop routing protocols AODV and OLSR. After the metric validations were done, routing metric specification of the two routing protocols used were provided.

1.4 Contribution of this Work

The main contributions of this work are:

- State of the art concerning movement impact on multi-hop routing:
  - This study was focused on analysing heuristics and metrics as well as routing protocol extensions that could improve routing in terms of path re-computation.
- Two families of new routing metrics, devised to be applicable to any shortest-path based wireless routing approach, and validated, via simulations, in the context of AODV and OLSR, the two main representative multi-hop routing protocols.
- ns2 software modules developed in C, under LGPLv3.0, publicly available [104]
- Specification for integrating the different metrics in any routing protocol, explaining how they have been integrated into AODV and OLSR.

Annex A provides a table containing a quantification of the achievements of this work, in terms of scientific indicators.

Chapter 2

Related Work

2.1 Wireless Architectures Evolution

Wireless architectures for communication systems have undergone a paradigm shift in the sense that architectures, which have traditionally supported end-users radio-enabled devices, are changing both in terms of topology, and in terms of application. In terms of topology, the networking architecture, has evolved to integrate access functions closer to the Internet user, for instance, incorporating routing and relaying features in end-user devices. Furthermore, due to the proliferation of wireless technologies, end-user devices are today wireless enabled, low-cost, and low-resource capable. A variety of user friendly multimedia enabled end-user devices have also increased. Mobile devices, equipped with different types of radio interfaces, are continuously increasing in popularity [99]. For instance, Cisco predicts that traffic from wireless and mobile devices will exceed traffic from wired devices by 2016, and over half of all IP traffic will originate from non-PC devices by 2018 [99]. Wireless architectures have therefore been evolving from the initial centralized infrastructure mode to more complex, multi-hop paradigms, facing requirements such as the need to adjust to frequent movement, energy constraints, or even low-resource node architectures.

An additional step towards user-centricity relates to architectures where end-user devices can play the role of a network node [72][28][63]. Not only does this encourage data exchange between end users , but it also allows such devices to connect among themselves in an autonomic way. Hence, today we have an Internet which is terminated in its majority by at least one wireless hop towards the end-user. In addition, on the fringes, such wireless architectures are not centralized and spread in a viral way, becoming naturally more dense, where the human population abounds, and sparse in remote locations. An example of this behavior is the Internet sharing feature present today in any operating system, which allows the Internet user to share its Internet access with other users. Devices carried by humans are a key part of these new architectures and since they are carried/controlled by humans, they are expected to exhibit some characteristics of human roaming social behavior [29][74], in particular in the way that nodes cluster or move. As a consequence, connectivity models are significantly affected by this new trend, and so is routing stability.

2.2 Single-Source Shortest Path Routing in the Internet

This section is dedicated to the explanation of basic notions concerning the de-facto routing on the Internet, i.e., single-source shortest-path routing. It should be highlighted that such addressing is highly relevant, given that single-source shortest-path routing is today applied to networks independently of technology (wireless or wired), and as a consequence, has significant impact on new types of Internet architectures. In the context of wireless networks, routing as a control plane process is required if nodes want to transmit information across more than one hop, to find the optimal path(s) towards the destination(s). Routing is a necessary process when nodes in a graph are connected by more than one hop, and when traffic is to be sent from sources to destinations by relying on intermediate nodes. Routing can be applied to find the optimal route to transfer information from one node to the other, according to pre-defined optimality criteria, e.g., minimum number of hops between a source and a destination. On *Open Systems Interconnection (OSI)* Layer 3, network elements (routers) rely on routing algorithms and protocols to compute paths that *Internet Protocol (IP)* packets (datagrams) will follow. Routing can, therefore, be defined as a process composed of the several components:

- Optimal path computation performed by a routing algorithm.
- Path storage performed by relying on a routing database (table).
- Path management and selection performed by a routing protocol.

In addition, routing relies on optimality criterion to assess which path(s) is/are considered the “best”. Therefore, routing relies on specific metrics to perform route selection. Examples of routing metrics can be the distance between source and destination, delay or available bandwidth to mention a few. Routing protocols are an embodiment of routing processes. Currently, and in regards to single-source shortest-path routing, there are two main families of routing protocols: link state and distance vector. These categories are better explained in the following sub-sections.

2.2.1 Link-State Routing

In *link-state (LS)* routing, each router builds its own perspective of network connectivity based on information periodically exchanged with neighbors. Each router then independently computes the best next hop from the router as source to every possible destination in the network.

For path computation, link-state routing relies on the Dijkstra’s shortest-path algorithm. Being derived from Dijkstra, the LS family achieves a converged topology view by following two steps: i) finding out a node’s neighbor (adjacency matrix); ii) distributing (flooding) a node’s topology perspective to every single node in the network. Due to this individual computation, if some nodes are not synchronized (e.g., they do not, at an instant in time, have the same map for the topology), routing loops will emerge and may disrupt a network heavily. Link-state information about a particular link in one part of the network to another part can transverse on a hop-by-hop communication basis to eventually spread it throughout the network (i.e., flooding). On receiving the link-state information, the node can do its own route computation in a distributed manner. A link-state message, often referred to as *Link State Advertisement (LSA)*, is generated by a node for each of its outgoing links holding the following information: source node identifier, link identifier, link cost, sequence number and age.

When the same node needs to generate a new LSA for the same outgoing link, it increments the sequence number, inserts the new value in the LSA message and sends it. A node discards an LSA with a low sequence number when a high sequence numbered LSA from the same node is received. The age of LSA decreases every time it is forwarded by a node, with the maximum lifespan when still at the source node. A typical link-state routing protocol consists of three sub-protocol mechanisms:

- HELLO exchange between neighboring nodes.
- Resynchronization mechanism.
- Link State advertisement.

The HELLO exchange is used to allow synchronization of information between neighboring nodes and is normally performed periodically. The re-synchronization mechanism is used to recover from a link or node failure. The re-synchronization mechanism is aimed at bringing the network to the most up-to-date state. The mechanism involves link state exchanges between neighboring nodes.

2.2.2 Distance-Vector Routing

The *Distance-Vector (DV)* routing family dates back to the predecessor of the Internet, ARPANET. In DV, a node needs to know the distance from its neighbors to a destination. The basic information exchange aspect about DV routing is that the node needs to know the distance information from each of its neighbors to all the possible destinations. With this information, it can compute the shortest path. DV routing, therefore, needs to address the dissemination and reception of information. The characteristics of DV routing are the following:

- The protocol does not need to know beforehand how many nodes are in the network; through the information received periodically that may contain information of the new node, the receiving node updates the list of destination nodes.
- For each destination node j, the protocol maintains/updates the next hop H_{ij}.
- With the arrival of DV information for node k, the protocol updates the cost to a destination if the currently stored next hop for this hop is also k.

As far as the exchange of DV information is concerned, its importance is assessed as the following:

- The order of receipt of the control information is important.
- The frequency of dissemination of the DV information is important.
- The instant at which the node broadcasts the DV routing information is important.

- The instant when the routing computation is performed is important
- The instant when the routing table is updated is also important.

With the above listed instances, times and frequencies, a routing environment may encounter a transient period when nodes have different perceptions of the network. Then, a network is said to have converged if the network nodes have the same perception about the network.

2.3 Routing in Wireless Networks

This secion focuses specifically on wireless ad-hoc routing, as our metrics have been devised to be applicable in wireless networks. In ad-hoc routing, all nodes act as routers to deliver the data in the network [45][38]. In addition, intermediate routers must be in promiscuous mode to accept any message they receive. A routing mechanism is then required so that data can be routed from a source to a destination [68]. The routing mechanism will govern on how path computation to the destination will be performed (routing algorithm); there is also the need for storage of the computed path and path management and selection. A routing protocol will then perform all the routing mechanisms required.

There are several ad-hoc routing approaches, normally categorized according to: i) the way information is propagated (based on Link-State or Distance-Vector approaches); ii) the way routes are computed (e.g., reactive or proactive); iii) the type of ad-hoc topology (flat or hierarchical), resilience (single or multi-path) [62][43][45].

Main ad-hoc routing categories are:

- **On-demand (reactive)** [62][70]

  Reactive routing protocols compute for a routing path when the path is required.

- **Table-driven (proactive)** [62][70]

  Proactive routing protocols are based on periodic exchange of information [32], and paths to destinations are periodically computed avoiding the need to compute for a path when it is required.

- **Flooding-based**

  Flooding-based routing protocols broadcast packets in order to learn the topology, or discover a path to a destination when none is known to exist [22].

- **Cluster-based**

  In cluster-based routing, nodes in a topology are grouped in clusters and one node is selected as a cluster-head, while other members of the group assume cluster membership. The cluster-head in responsible for intra-cluster transmission and data forwarding [47].

- **Geographic**

  In geographic routing, packet forwarding decisions are based on node position information. As such, messages are routed towards the position of the destination node. The nodes in geographic routing do not maintain a routing table [44].

Multi-hop routing is faced with the challenges resultant from a wireless medium. In a wireless channel, as a receiver moves over a short distance, the signal strength may vary rapidly, due to the multi-path propagation effects: this is called *small-scale* fading. As the receiver moves away from the transmitter over a larger distance, the local average signal strength gradually decreases. This is called *large-scale fading* [5]. Furthermore, wireless network nodes are bandwidth constrained, with variable link capacity as the nodes move dynamically also due to small scale fading, the nodes are resources and energy constrained as they mainly operate on battery power, have also a limited transmission range, and they may appear or disappear in the networks at any time.

In order to better address these issues and understand how multi-hop routing works, the next sections describe the most popular multi-hop routing protocols: AODV [7] and OLSR [32]. These two routing protocols are still the most popular and widely used [82][65].

2.3.1 Ad-Hoc On-Demand Distance Vector (AODV) Routing Protocol

AODV is an OSI Layer 3 on demand routing protocol based on DV, i.e., routes are only made available as they are needed. The description of AODV provided in this section relies mainly on the work of Belding-Royer and Perkins [7]. Routes are discovered through a route discovery cycle, where the network nodes are queried in search of the route to the destination. When a route is discovered, it is reported back to the source node. A control message *Route Request (RREQ)* is broadcasted during route discovery to all neighbors, and a node which is a destination or a node that has a valid route will respond to RREQ through a *Route Reply (RREP)* unicast message back to the source node. In case of link failure, a node sends a *Route Error (RERR)* to the neighbors that have the affected destinations in their routing tables. AODV also recurs to the regular DV operation, namely, it relies on a HELLO exchange between neighbors for link failure detection and monitoring. Because the wireless media resources are limited, AODV attempts to minimize the control overhead by eliminating periodic routing updates. AODV provides nodes with the ability to discover paths to the destination and maintain paths even when the network topology is changing. Routing loops are mitigated through the use of sequence numbers.

Some of the enhancements of AODV are Quality of Service (QoS) awareness, mobility awareness and energy awareness. Yassein *et al.* incorporated mobility awareness in AODV by using mobility metric *node velocity*, selecting nodes with low velocities for routing [89]. Sambasivan *et al.* proposed route state awareness in terms of mobility, by deriving a mobility prediction metric and adding a *Mobility Prediction (MP)* value to control packets in AODV (RREQ and RREP) [67]. *MP* is obtained by probing (heartbeat packet) both during route discovery and route maintenance. This enables the source to capture the stability of the links during route discovery. During route maintenance, a source sends a packet called *heartbeat* which learns the links signal strengths making up a path: if one path degrades, the next best path is used. Jamali *et al.* proposed QoS awareness in AODV by using route lifetime, residual energy and hop count during route discovery [33]. Santhiya and Arumugam used multi-path approach to introduce QoS awareness in AODV [69].

AODV and Mobility-awareness AODV relies on hop count to compute an optimal path. In its native form, AODV is therefore not sensitive to node mobility, since the resulting shortest pathmay not be stable as all nodes in it may be moving. The consequence may be frequent path recomputation. Then, in dynamic environments such as UCNs where node movement is frequent, AODV performance is bound to decrease in the presence of topological variability having as consequence frequent path re-computation. At the time of this work, there were already several enhancements of AODV which attempted, to some extent, to integrate mobility-awareness [67][55][89][39]. However, the mobility parameters used in such related literature in routing to capture node mobility did so partially. For example, Khamayseh *et al.* used pause time to determine the suitability of a node as a successor [39]. Pause time, as a mobility parameter, does not capture stability of nodes that exist when they are mobile. We provide a discussion on mobility capturing and mobility awareness integration in routing protocols in sections 2.4.3 and 2.4.4. We analyse the role of different mobility parameters to capture mobility in chapter 3.

As AODV is still the most popular DV multi-hop protocol [82][65], it is highly relevant to understand how to integrate mobility-awareness in its architectural design, in a way that is backward compatible with native (hop count based) AODV.

Advantages and Disadvantages of AODV Being a DV protocol, AODV inherits the advantages and disadvantages of Bellman-Ford based approaches. In terms of advantages, it is a robust algorithm with low overhead when the network is stable, it reacts quickly to topological changes and has a low setup delay. This occurs as AODV does not discover a route until a data flow is initiated. Another advantage of AODV is the application of sequence numbers to mitigate routing loops. There are, however, some aspects of AODV which require improvement. First and foremost, the intrinsic property that makes AODV a robust protocol (updates spread on a node-by-node basis) implies that AODV does not quickly reflect changes in the topology.

2.3.2 Optimized Link State Routing (OLSR)

OLSR is a version of the pure proactive link-state routing tailored for ad-hoc networks running on OSI Layer 3 [32]. It has been optimized to reduce network overhead induced by the control traffic [60]. The description of OLSR provided in this section relies on the work of Jacquet *et al.* [32]. OLSR is a table-driven routing protocol. Because of the proactive or table-driven nature, there is periodic exchange of control information to maintain topological information at each node. Some messages are sent locally to enable a node to know its neighborhood, and some are sent into the entire network which permits exchange of topological knowledge in the network. Routes are readily available to all destination nodes before there is the need to route to a particular destination. The route discovery latency experienced in on-demand routing protocols is usually larger than in link-state ones. OLSR employs two types of periodic control messages: HELLO message is used for link sensing and neighbor detection while the *Topological Control (TC)* messages are used for topological change updates. However, because the control messages are broadcasted in the network, bandwidth consumption by the control messages is high, which can affect overall network throughput. In line with this, OLSR was designed to optimize the number of control messages by introducing *Multipoint Relays (MPRs)*. Only the nodes selected as MPR by a particular node will forward control information for the node. MPRs are nodes that are selected by a particular node to broadcast a control message that a particular node will generate. The selection criterion is such that a minimum number of one-hop neighbors that enables the node reach to all two-hop neighbors is attained.

OLSR Optimization

OLSR, in its original definition, does not include any sensing for link quality and assumes that links are either working or failed, i.e., it still assumes a pure hop-count approach. A number of enhancements to the native OLSR have been proposed. Benzaid *et al.* proposed fast OLSR to enable a fast moving node to quickly discover a small set of neighbors for its tracking and reduction of packet losses [9][8]. Node mobility is detected with the rate of change of neighbors, i.e., with variations of node degree. A node with high mobility will change its neighbors frequently. Given that tracking of highly mobile nodes is difficult with default HELLO messages of the OLSR, which may result in packet losses for the mobile node, fast OLSR employs a higher frequency of the HELLO messages for the fast ones.

QoS aware selection of MPRs has also been proposed to make routing in OLSR QoS-aware [50][23][73]. De Rango *et al.* proposed an energy-aware selection of the MPRs mechanism to avoid rapid exhaustion of energy for a small subset of nodes in the network due to heavy traffic load, *Energy-Efficient OLSR* [25]. In Energy Efficient-OLSR, each node calculates its own energy consumption status to declare its appropriate willingness to be selected as an MPR. The willingness selection is based on battery capacity and predicted lifetime metrics. Overhearing by the nodes has been excluded to achieve higher energy saving. Data packet forwarding is also based in some energy metrics (e.g., *Minimum Battery Cost Routing*, *Minimum Total Transmission Power*).

OLSR and Mobility-awareness OLSR is a relevant example of a multi-hop approach based on LS [82][65]. This routing protocol uses hop count to select MPR nodes. The protocol also suffers from lack of node mobility sensitivity as the routing metric of hop count is agnostic to node mobility. Related work has addressed ways to optimize MPR selection, by integrating some level of mobility-awareness in such selection (e.g. an MPR may disappear of the network). However, the level of sensitivity the protocol attains depends on the attributes of the mobility parameters used. For example, Benzaid *et al.* used the rate of change of neighbors to detect node mobility [8]. The parameter is agnostic to node mobility when the number of new neighbors equals that of link breaks, as neighbors leave. We provide a discussion on mobility capturing and mobility awareness integration in routing protocols in sections 2.4.3 and 2.4.4. We also analyse to which extent the mobility parameters capture mobility in chapter 3.

Advantages and Disadvantages of OLSR

The proactive nature of OLSR assists in reducing latency during route discovery, a challenge to on-demand approaches, such as AODV. OLSR inherits fast convergence from link-state routing due to the greedy exchange of updates. In contrast to the regular LS approaches, which incur high levels of control overhead due to flooding, OLSR avoids this disadvantage by using of MPRs [60]. However, OLSR periodic updates do not cater for high mobile nodes. This results in high packet losses and more retransmission, in turn affecting the network throughput. In a network with high spacial dependency among the nodes, OLSR will perform better as the rate of link breakages is low and the routes in the routing tables can be still used. The nodes have long network routing tables, which reduce the computational performance of the nodes.

2.4 Node Mobility in Multi-Hop Routing

The previous section described multi-hop routing and provided categories and examples of multi-hop routing protocols. This section discusses node mobility in relation to multi-hop routing to assist the reader in understanding node mobility characteristics and how they impact routing. The section also covers a discussion on works dealing with node mobility tracking, as well as how routing protocols can become mobility-aware.

2.4.1 Impact of Node Mobility on Routing

To understand the impact of node mobility on routing performance, Das *et al.* used the mobility parameter *pause time* [24]. By varying the pause time of nodes in a topology, they noted a high number of link breaks in topologies where nodes exhibited in average a short pause time when compared to topologies where nodes held, in average, longer pause times. A shorter pause time means that there are higher levels of uncorrelated mobility among nodes, which introduces more link breaks compared to more static nodes (higher *pause time*) in topologies. Javaid *et al.* have evaluated also the impact of node mobility on a number of multi-hop routing protocols of reactive and proactive categories [34]. The authors observed that reactive routing protocols performed better in terms of mobility constraints, when compared to their counterparts belonging to proactive routing group. Bai *et al.* showed that the extent mobility has on routing performance is dependent on the building blocks of a routing protocol (i.e., route setup phase, route maintenance phase) and mobility patterns [6]. Panda *et al.* studied the impact of node mobility and terrain size on two reactive routing protocols, AODV and *Dynamic Source Routing* when applying random waypoint mobility [61]. Their findings were that routing protocol AODV outperformed DSR in high mobility scenarios [35]. This can be due to the fact that DSR is a source-based routing protocol that can suffer from stale routes in highly dynamic environments.

The impact of different mobility patterns on multi-hop routing protocols has also been studied. Liang *et al.* studied the impact of node mobility on video transmission over wireless multi-hop networks [53]. They show that node spatial correlation has the ability to improve video quality and reduce the transmission delay without the help of advanced video coding techniques. This can be due to lower mobility variability among spatially correlated nodes, ultimately incurring fewer link breaks. Divesha *et al.* studied the impact of different mobility patterns on routing performance, obtained from different mobility models [26]. They studied performance of one reactive routing protocol, DSR, and one proactive routing protocol, *Destination-Sequenced Distance-Vector (DSDV)* [54] under different mobility models. Varied performances of each routing protocol were obtained using different mobility models, meaning that node mobility patterns affect routing performance differently. This is affirmed by the study carried out by Hrudya *et al.* [30]. They have noted also that the routing protocols performed better under one mobility model, *Reference Point Group Mobility (RPGM)* [109], compared to other models used. This can be due to the fact that in the RPGM model, nodes move in groups [26] meaning that there is a high temporal and spatial correlation among the nodes, thereby resulting in fewer links breaking due to node mobility. It was also noted that routing protocols, DSR and OLSR, were the worst affected in terms of high variability of performance across different mobility models. This could be due to the differences in routing protocol architectures, as mentioned above. DSR employs source routing and stale routes become more prevalent in dynamic environments. Kmuar and

Shama analysed the impact of mobility patterns obtained from different mobility models on the performance of reactive and proactive protocols [42]. Their analysis, like the Bai *et al.* study [6], shows how mobility impacts the different routing building blocks.

In this section, we have discussed the impact of node mobility on multi-hop routing, where node mobility pattern plays a role in the extent that multi-hop routing is affected by node mobility. The section also highlights works discussing how routing protocol architectural composition affect routing performance in the face of node mobility. It is worth to mention that the analysis of mobility impact so far has been limited to older mobility models (such as random waypoint - RWP) which are today known not to be relevant when considering devices that are carried by humans. In these environments *social mobility models* should be applied, as these models incorporate statistical properties of human movement behavior. To better understand the impact of social mobility characteristics in routing, in the next sections, we discuss characteristics of human mobility and studies that have explored human mobility effects on multi-hop routing and how we believe they can impact routing performance.

2.4.2 Node Mobility in UCNs

This section discusses mobility aspects that relate to the patterns that nodes have in UCNs. In networking, modeling of mobility (modeling which dictates choices concerning routing architectural design) has been based for some time in models integrating Brownian motion approaches. More recently, some authors attempted to understand better the characteristics of human movement [29][74]. These studies revealed that the way humans move is not random, but it has a high degree of temporal and spatial periodicity. Gonzalez and Barabas relied on traces covering the trajectories of 100,000 anonymous mobile phone users collected during six months, and proved that individual human trajectories have a high degree of temporal and spatial regularity [29]. According to the authors, individual trajectories observed are characterized by a time-independent travel distance and a significant probability to return to a few preferred locations. They also found a strong tendency in humans to return to locations they visited before (*visited networks*).

Also based on traces, Kim and Kotz observed periodic properties based on short-term (1 month) and long-term (1 year) observations on a large university campus (Dartmouth university, USA), of end-users and *Access Points, (APs)* [41]. The authors showed that there is a periodic behavior for both end-users and APs on a daily basis, and a weekly periodic pattern is observable only for APs. Based upon the long-term traces, the authors inferred properties that relate to the academic calendar and also to the end-user proximity (physical proximity at an instant in time) to APs. The most interesting contribution relates to a framework which can be applied to other traces, to extract periodic properties and to translate them into a statistical formulation. Song *et al.* studied to what degree human mobility is predictable [74]. Using anonymous mobile phone users to study human dynamics, they found 93% potential predictability in user mobility.

Related work concerning human movement and its modeling shows that such movement has a tendency for some level of periodicity (routine); a tendency to spend more time in preferred locations; a tendency to prefer short distances instead of long distances. These studies have been initially applied in the context of *Delay-Tolerant Networks (DTNs)* and opportunistic routing. For example, Boldrini *et al.* analysed the impact of human mobility on opportunistic routing [11]. Nguyen *et al.* studied the temporal dimension of human-centric disruptive tolerant networks and how routing performance is affected [59]. Chaintreau *et al.* studied the impact of inter-contact times of human mobility patterns on opportunistic routing [12].

2.4.3 Capturing the Extent of Node Movement Impact in Routing

With the study of the impact of node mobility in section 2.4.1 and 2.4.2, we note that it is important to capture node mobility so that routing protocols become fully aware of the underlying node mobility characteristics. This section discusses studies that have aimed to capture node mobility extent to make routing sensitive to node mobility.

Node Mobility Parameters

Due to the negative effect node mobility can have on routing performance, mobility parameters have been devised to capture the extent of node mobility to make multi-hop routing sensitive to node mobility. A relevant number of suchmobility parameters are: *link duration; number of link breaks; pause time* [42][90]. Yawut *et al.* provided a discussion on the desired characteristics of a good mobility parameter/metric to indicate protocol performance, as being protocol independent and feasible to compute [90]. From their analysis of different mobility parameters, they endorsed the parameter *Link Duration* as the best. However, Link Duration as a parameter is somewhat agnostic to mobility patterns. Liang and Thomas also studied different mobility parameters and also highlighted the need of a mobility parameter to be protocol independent, as in the Yawut *et al.* study [90], and to be scenario independent [52]. They endorsed the number of link breaks as the best mobility parameter. Kumar *et al.* classified different mobility parameters into two categories of direct and derived mobility parameters [46]. Under the direct category, they include physical parameters such as *speed*, *degree of temporal dependency* and in the other category, it includes parameters such as *link duration* and *number of link breaks*.

Works on analysis of individual mobility parameters have also been done [71][79]. Shu and Li endorsed *link failure rate* as a good mobility metric in their work, where a mobility model used was a simplified version of RWP [71]. Nodes with high link failure rate on a data carrying path led to high number of path re-computation and control overhead, ultimately affecting routing performance. They argued that there is a relation between link failure rate and average speed of the nodes in a topology. This relation is, however, mobility pattern dependent. For example, in highly correlated nodes, like wireless devices acting as nodes on a moving bus, average node speed does not correlate with link failure rate. Tran *et al.* in [79] argued that the parameter/metric is the number of node dependence (i.e., if nodes are many in a topology, link failure rate will be higher than in scarce topology for the same kind of mobility patterns for the node [79]).

In this section, we provided an overview of works that have aimed to capture node mobility to make multi-hop routing more sensitive to node mobility. In chapter 3, we discuss in details the sensitivity of mobility parameters to node mobility. We believe that adequate capturing of node mobility is important for increased robustness of routing protocols to node mobility.

2.4.4 Mobility-awareness Capability in Multi-hop Routing

Section 2.4.3 described works that aimed at capturing the extent of node mobility to make routing protocols sensitive to node mobility. This section describes works that aim at node mobility awareness integration in routing protocols with a view to make routing more robust in dynamic environments using different mobility parameters.

A first category relates to applying signal strength measurement at the receiver as a way to estimate node mobility. In such category, Meng *et al.,* in their *Mobility Prediction Ad-Hoc On-Demand Distance Vector (MAODV)* routing protocol, have considered variations of the received signal power by a particular node which, associated to a propagation model, assisted the authors in predicting its motion. Hence, they attempted to understand (based on node speed) when a link could break [55]. Such estimate allowed to reduce delays, at the cost of increased signaling overhead and lower throughput. Therefore, *MAODV* is one of the approaches attempting to make on-demand multi-hop routing more sensitive to node movement; however, it is not able to capture the diversity of different node movement patterns, and hence, it can result in higher signaling overhead. Dube *et al.* also used signal strength as a way to capture better links and develop more robust paths [27]. A link is considered stronger than another if it exhibits better signal strength for a longer duration than the other. Their approach is, however, only related to the route discovery phase, and hence, links that are affected by node movement on a later routing phase are not monitored. Received signal strength, as a way to detect node mobility, does well but is somewhat agnostic to some mobility patterns that may exist.

Another category of work relies on *link sensing* as a measurement of improving routing in terms of mobility sensitivity. Sambasivan *et al.* proposed route state awareness in terms of mobility, by deriving a mobility prediction metric and adding a *Mobility Prediction (MP)* value to control packets in AODV (RREQ and RREP) [67]. *MP* is obtained by probing (heartbeat packet) both during route discovery and route maintenance. This enables the source to capture the stability of the links during route discovery. During route maintenance, a source sends a packet called *heartbeat* which learns the links signal strengths making up a path, such that, should one path degrades, the next best path is used. Albeit relevant for the specific case of AODV, heartbeat packets introduce additional overhead and yet, there is still no distinction between a true link break, or a temporary break. Benzaid *et al.* proposed the *fast Optimized Link State Routing Protocol (fast-OLSR)* whose basic idea was to detect link changes in a quicker way, by increasing the HELLO sending rate [9]. Such HELLO messages only include *MultiPoint Relay (MPR)* node information and the neighbors selected as *MPR*s reply with empty fast HELLO messages with the same frequency. Fast-OLSR has its own shortfalls as the fast HELLO messages introduce more overhead, and considering the rate of change of neighbors to measure mobility may be misleading in cases where a static node is bypassed by a surge of mobile nodes. Some nodes will change neighbors of the same set; for instance, a node with a circular motion among static nodes can be changing neighbors frequently among the same neighbor set. If that can be captured, routing overheads can be reduced.

Node neighborhood changes has also been studied to capture node mobility. Lang *et al.* obtained node spatial correlation by monitoring the ratio of changing neighbors to detect node stability [36]. Wenqing used transmission radius overlap between nodes to determine link and path stability [84]. Chen and Lee devised a scheme based on link duration to capture stable links [20]. *Link expiry time* has also been used as one of the routing metrics to make routing protocols mobility aware. Hu *et al.* proposed a stability enhanced algorithm that employs *Link Expiry Time (LET)* to capture routes with the highest minimum LET of the links in the *route requ*est *(RREQ)* [31]. Yassein *et al.* incorporated mobility awareness in AODV by using mobility metric *node velocity*, selecting nodes with low speed for routing [89]. While velocity (speed) is a good mobility metric to distinguish link stability in scenarios comprising fast and slow moving nodes, it does not capture stability that may exist among fast moving nodes, for example nodes in group mobility.

Other than mobility aware metric integration in existing multi-hop routing, a number of new mobility aware routing protocols have been created. Akunuri *et al.* devised a mobility multi-hop routing protocol based on node LET [4]. Using node LET, a decision on whether a node can be included on a route during route discovery is made. Nodes with low values of LET are avoided as successor nodes in new routes. This is aimed at prolonging route lifetime. However, LET, as a mobility parameter, fails to capture long term mobility patterns that may exist in a topology. Sujang and Evans devised another multi-hop routing protocol based on link break prediction to trigger route updates [76]. Khamayseh *et al.* devised a mobility and load aware routing protocol where nodes decide whether to broadcast or drop RREQ messages based on their speed and routing load during route discovery [40]. Creixell and Sezaki devised yet another mobility aware routing protocol based on node mobility prediction by monitoring changes in inter-node distance [21]. Since these are new routing protocols, it would imply having them ready in all nodes in the network, as they are not backward scalable. Having routing metrics implemented on two popular routing protocols increases their applicability.

This section discussed works that have integrated different mobility parameters/metrics into multi-hop routing to make routing more robust to node mobility. As mentioned above, how robust a routing protocol becomes to mobility depends on the sensitivity of mobility parameter/metric used to capture mobility.

2.5 Node Mobility Patterns and Mobility Models

Mobility modeling, analysis and simulations are essential to an adequate design and evaluation of mobile networking protocols, services and applications [77]. When real node mobility cannot be obtained, use of mobility models to mimic node mobility is one option. In case of social oriented node mobility, Thakur *et al.* discussed the importance of adequate human mobility characterization in social mobility models for realistic reproduction of human mobility effect on networking performance [78]. Existing human mobility models have been analysed to determine their adequacy in capturing human mobility characteristics [37][77]. Based on their analysis, Thakur and Helmy proposed a new mobility model *COBRA* [77].

Musolesi and Mascolo gave insight into current mobility modeling aspects from a community perspective which follows the way humans build their networks of trust (social networks) [58]. They provided a survey concerning the group mobility models, and presented a new approach to model human behavior. The same authors proposed a mobility model, *Community-based Mobility model (CMM)*, that mimics how humans tend to move and group in communities based on social relationships among individuals. The properties derived and observed in traces seem to be relevant to make routing more adaptive to mobility.

Lee *et al.* provided a mobility model, *Self-Similar Least-Action Human Walk (SLAW)*, characterized on human walk properties [48]. These properties are truncated power-law distributions of flights, pause-times and inter-contact times, fractal way-points, and heterogeneously defined areas of individual mobility.

2.6 Quality of Service and Energy Aspects in Multi-hop Routing

To support multimedia and other applications, it is desirable that an ad-hoc network has the capability to provide acceptable levels of Quality of Service (QoS) [3]. End-user devices, which act as networking nodes, have limited resources in terms of energy. As such, other than high nomadic movements of nodes in mobile environments, energy and QoS are important aspects that need to be addressed for adequate service delivery. There also exists a relation of node mobility to QoS and node energy consumption. In this section, we review works that aim to improve QoS of a multi-hop network topology. Nodes in multi-hop topologies have low energy resources and require that their energy consumption be minimal to prolong nodes lifetime and ultimately network lifetime. Among energy consuming procedures of a network node are packet transmission and receipt. Control overhead in a topology contributes to the depletion of the node energy resources as control packets are sent and received by network nodes in a topology.

2.6.1 Quality of Service and Multi-hop Routing

QoS is a measure of level of service that data gets from a network [83]. Bandwidth, delay, jitter and probability of packet loss are some of the attributes of QoS. A network is expected to guarantee some level of service from different applications. In case of MANETs, the provision of required level of QoS is posed with a number of challenges. Some of the challenges are [83]:

- Varying physical link properties due to fading.
- Media Access issues due to shared channels among devices.
- Network topological changes and link characteristic changes due to node mobility.

Nodes in MANETs use multi-hop routing to transfer data from one node to another due to limited communication range of nodes. To achieve the required QoS, routing paths should have available resources meet the QoS constraints [51]. A number of approaches to incorporate QoS awareness in multi-hop routing protocols are presented in [91][66][83].

To deliver the required level of QoS for different applications, a number of multi-hop routing protocol extensions have been proposed. Jamali *et al.* proposed QoS awareness in AODV by using route lifetime, residual energy and hop count during route discovery [33]. Santhiya and Arumugam used multi-path approach to introduce QoS awareness in AODV [69]. Zafar *et al.* used an estimate of residual link capacity to allow call admission in DSR [91]. Some of other QoS awareness approaches are minimum delay, minimum loss, expected transmission count and bandwidth [10][23].

2.6.2 Energy and Multi-hop Routing

Nodes in multi-hop routing protocols have low energy resources as they are mostly battery powered. It is therefore important to understand the works performed to optimize energy consumption. De Rango *et al.*, in OLSR, proposed an energy-aware selection of the MPRs mechanism to avoid rapid exhaustion of energy for a small subset of nodes in the network due to heavy traffic load [25]. In Energy Efficient-OLSR, each node calculates its own energy status, to declare its appropriate willingness to be selected as an MPR. The willingness selection is based on battery capacity and predicted lifetime metrics. Overhearing by the nodes has been excluded to achieve higher energy saving. Data packet forwarding is also based in some energy metrics (e.g., *Minimum Battery Cost Routing*, *Minimum Total Transmission Power*). Packet transmission and receipt are some of the procedures where node energy is consumed [57].

2.6.3 Impact of Node Mobility on QoS and Energy Consumption in Multi-hop Routing

Node mobility causes changes in wireless links in terms of capacity as well as topological changes as links break. Frequent changes in network topologies make QoS sustenance difficult, since paths for routing data are short lived, and routing performance is affected due to frequent path computation in route discoveries. Perkins *et al.* argue that mobility-induced path failure increases packet loss rates, end-to-end delay, and communication overhead, and that it is a key obstacle to improving QoS in ad-hoc networks [64].

Mohsin *et al.* discussed packet transmission and receipt as some of the procedures where energy is consumed [57], Energy Efficient Location Aided Routing protocol, to reduce energy consumption, and reduce the area for new route discoveries. This reduces control overhead in a network topology [56]. Node mobility, as mentioned above, causes wireless links to break. A link break on a route results in data transmission disruptions and a multi-hop routing protocol, when used, computes for an alternative path. Frequent path re-computation increases control overhead, which ultimatey consumes more energy in terms of packet transmission and reception.

2.7 Summary

This chapter described the current wireless architecture evolution where end-users are empowered to become network connectivity providers, such as UCNs. There is also a recognized increase in the number of end-user devices. These end-user devices can act as network nodes. Due to their limitation in communication range, multi-hop routing is used to compute paths for data transfer. We have provided notions concerning single-source shortest-path routing in the Internet and in ad-hoc networks. Then, this chapter described related literature focused on analysing the impact of mobility on routing, paying special attention to how different mobility patterns affect routing. We also provided a summary of studies aimed at characterizing human mobility patterns which are prevalent in user-centric environments. The analysis provided showed that such studies mostly target DTNs, leaving a gap for topologies that are not delay-tolerant. The capability to track node mobility in a non-intrusive way plays an important role on how robust a routing protocol becomes in regards to mobility on a network. Therefore, in this chapter a review of works that have integrated mobility parameter/metric has also been provided. The chapter debated also on other important aspects of multi-hop routing, namely, QoS and energy-awareness, and we have presented our view concerning the relation to mobility-awareness.

Chapter 3

Mobility-Aware Routing Metrics

This chapter corresponds to the core of our work and proposes mobility-aware routing metrics that have been created in an attempt to be applied to any shortest-path based routing approach, past and future. The chapter starts by explaining how node movement impacts routing (under which conditions and requirements), and it then addresses the relevance of different networking parameters that can be taken into consideration to derive mobility-aware metrics. Then, based on these parameters, the chapter describes our proposed metrics which are categorized into two distinct sets: *time-based* and *node spatial correlation based*. Routing metrics falling under time-based family take into consideration link activities, such as the number of link breaks a node incurs over a period of time to determine its suitability as successor. Spatial correlation-based family comprises metrics that employ nodal neighborhood perspective to capture the level of stability and ultimately node suitability as successor on a routing path. This chapter also covers the design and rationale for each devised metric, as well as the algorithms to apply the metrics in DV or LS routing protocols. The chapter concludes with a summary and an explanation of the differences between each of the metrics.

3.1 Multi-hop Routing Adaptability to Node Mobility

3.1.1 Approaches to Capture Node Mobility

In order to better characterize routing sensitivity to node movement, we provide in this section notation that shall be used in the next chapters.

It is assumed here that nodes i and j are adjacent in some moment in time; the link between i and j is defined as *(i,j)*; both nodes can move. When node i or j moves, a topology change occurs and one out of three situations may occur:

1) This movement is not significant and does not affect routing computation.

2) This movement is significant and affects routing computation.

3) This movement is not significant, or corresponds to, e.g., a ping-pong movement, and yet affects route re-computation.

One of the aspects that we have addressed in this work is the meaning of a "significant" impact in routing. Another aspect is to understand the impact of route re-computation due to mobility.

The impact of node movement on route computation relates today to the perceived signal strength by a receiver node. Node movement is heavily related to distance between nodes and *Signal to Noise Ratio* (SNR) is correlated with inter-node distance. When SNR falls below a predefined threshold, a link between the two nodes is said to be broken [92]. Today multi-hop routing triggers path re-computation based on a node's perception of a link break.

However, this does not suffice to assist a robust protocol in the event of dynamic, mobile nodes, as some nodes may have considerable stable links tending to spend some considerable periods in each other´s communication range (for example, two end-user devices in a home, but in the evenings and weekends they are in each other's proximity). Therefore, our belief is that an adequate routing metric must be able to:

1) Anticipate node movement pattern.

2) Understand the node movement in regards to its neighbors.

By being able to devise such a metric, it is feasible to add it to a multi-hop routing protocol, independently of the family (be it link-state or distance-vector based). Our expectations are that path re-computation becomes optimized and the consequence is a reduction in signaling overhead and an eventual increase in throughput. Latency is also expected to be reduced due to two main aspects: a lower signaling overhead, and an optimization of the path selection process.

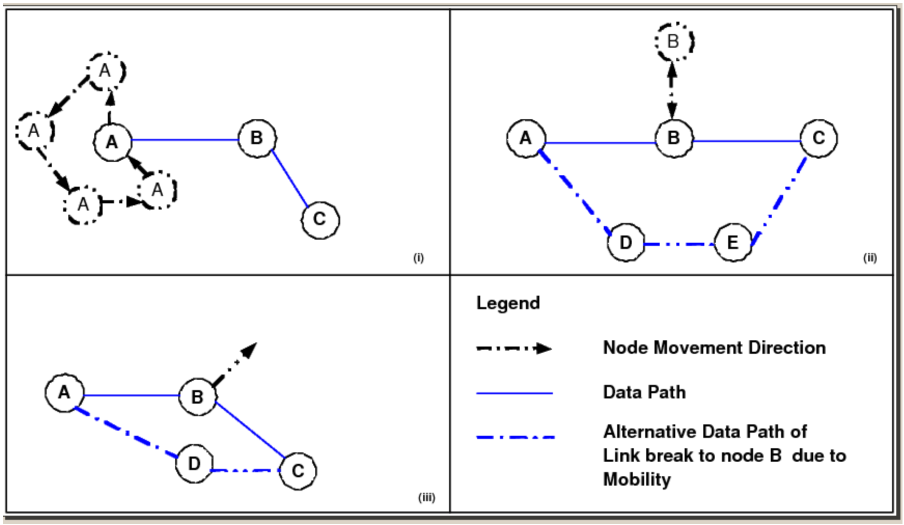


Figure 3.1: Node Mobility Example.

3.1.2 Analysis of the Impact of Node Mobility on Routing

The impact of node mobility on routing can be measured mostly by analysing the trade-off in robustness (e.g., the need to re-compute more paths) vs. signaling overhead (more messages sent to detect link breaks in a smaller time). Furthermore, node mobility impacts routing in different ways, and this section addresses the main ones, namely: relation to distance, movement pattern (and how it affects links), relative movement (link remains stable due to similar movement of the nodes that compose the link), impact on the different stages of the routing process (e.g., route discovery and maintenance phase).

To give a concrete example, let us consider Figure 3.1 which illustrates a wireless topology where A and B represent nodes in motion. The figure considers three different cases. In Figure 3.1 i), A exhibits a confined movement, eventually returning to its original position. In figure 3.1 ii), B is the node moving in a ping-pong pattern, i.e., B is jumping back and forth between two different positions. This stands for a case of repetitive movement, where the node exhibits some pattern on the frequency of moving away/returning to origin. The final case (cf., Figure 3.1 iii)) corresponds to the case where B permanently moves away from its original position. Upon movement of at least one of the nodes A and B, the corresponding link quality is affected. If the nodes exhibit frequent movement, frequent path re-computation may occur.

The impact of node mobility on routing is also distance dependent, i.e., related to link size.

For instance, a link formed by two nodes far apart (long link) can be affected and broken even by a small, insignificant node movement. If instead we have a short link (small distance between the two nodes), the movement of a node has to be significant to result in a link break. It should be noticed that link quality may degrade also due to mobility, but what we are highlighting here is that changes in distance are not sufficient to define a routing metric sensitive enough to node movement. It is also necessary to incorporate some sensitivity to a node's movement pattern and this is not a trivial task given the possible mobility patterns. For instance, a node moving between two different positions A and B can just move from A to B; move away from A to B and come back to A; or it can be ping-ponging between A and B. As mentioned previously, such movement pattern may be insignificant in terms of impact on a link (e.g., because the distance between the nodes is short). In contrast, a movement between A and B will impact link capacity heavily, and a ping-pong movement will result in a wide wireless link capacity variation.

The Impact of Node Mobility on Multi-hop Routing Phases

Another aspect to consider in terms of impact of mobility on routing is the routing phase where the movement is detected. Of utmost relevance is node mobility during the route discovery and route maintenance phases. In relation to mobility impact, the most relevant routing processes are: route discovery, where a route to a particular destination is not known and has to be built and computed; and route maintenance, where routes are maintained and re-computed. For instance, if a link on an active route breaks, an alternative route to the destination is computed and this is done during the route maintenance phase. Assuming the existence of a link considered during route discovery, where one of the nodes is moving, it may happen that the resultant path of route discovery is not available as the link would have been broken. Routing protocol under route maintenance will have to re-compute an alternative path for data transfer. To further debate on the impact that node mobility has on the routing process, it is discussed, in subsequent paragraphs, the impact of movement during route discovery and maintenance. We start by addressing such potential impact by analysing different parameters, to then understand the potential impact on the two most popular multi-hop routing families, distance vector and link state, which are represented here, by the *ad-hoc On-Demand Distance Vector (AODV)* and the *Optimized Link State Routing Protocol (OLSR)*, respectively [7][32]. The explanation provided next has as main purpose to explain in further detail the impact of node movement on routing.

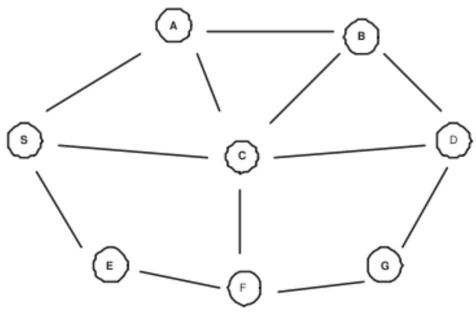


Figure 3.2: Simple Network Topology Example.

Impact of Node Mobility on The Route Discovery Phase

Considering AODV, during the route discovery, a node (i.e., source node) upon demand broadcasts *Route Request (RREQ)* packets. A reply in the form of a *Route Reply (RREP)* will be returned as soon as a node realizes it has a route established to the destination. We assume node movement of the source node, or the movement of any of the nodes on the path before a reply is received by the source node, i.e., before a path is fully established. This may result in path establishment failure, depending on the type and pattern of movement of the source node and the intermediate node. To what extent node mobility will impact the route discovery phase depends on several aspects, for instance: whether a link is short or long, the mobility pattern, frequency of motion and also the node degree. The number of nodes moving as well as the sequence of node displacement from the original positions is also relevant to address.

To assist the explanation of the impact of node mobility on route discovery, Figure 3.2 shows a topology where a route has to be discovered from Node S to node D, where, based on hop count, the path between S and D should be S-C-D. A number of alternative paths also exist but are longer, for example paths S-A-B-D, S-A-B-C-D and S- E-F-G-D to mention a few. Let us consider that nodes A and B exhibit some form of confined movement as shown in Figure 3.1 i), and node S broadcasts a RREQ for route discovery. Let us also assume that only C and G know about the whereabouts of D. The RREQ sent by S may, due to such confined movement, reach C later than it reaches G. Therefore, the answer in the form of a RREP may result in a route that may be formed earlier and may actually be the longest, and the shortest may appear to be longer, for example, having a path of S-A-B-C-D instead of S-C-D. The impact of movement in this phase is, therefore, related to the type of movement, but also related to the type (short or long) of the link. If the links affected by confined movement are long, then the node movement will affect more significantly the path re-computation and adequate route discovery. If links are short, then movement of nodes in a confined area may not even be noticeable from a routing process perspective. However, if we consider some movement pattern which exhibits some regularity, such as the one in Figure 3.1 ii), then the frequency of regular movements significantly affects the route discovery independently of the links being short or long.

We have discussed the impact of confined node mobility on route discovery, and now let us debate on the frequency of regular node movement and how, in our opinion, it impacts the routing process in terms of route discovery. The three cases of node movement presented in Figure 3.1 may exhibit some frequency which implies that the node crosses its original position at some instant in time. By low frequency of movement is here meant that the node crosses its original position seldom; by high frequency it is meant that the node crosses its original position often. Assuming a confined movement scenario for a node with low frequency of movement, route discovery is barely affected with such node mobility whether long links or short links, while high frequency of confined movement impacts more on long links than short links. However, if we consider a movement pattern such as a ping-pong movement, then the impact of such frequency may in fact severely affect the route discovery phase, leading to routes that are not shortest-path based or even delaying such phase in a significant way as both short and long links are affected. Such delay is highly related to the network composition and node degree, in particular on the degree of the nodes exhibiting movement. Moreover, it is also highly related to the relation of the movement that a node exhibits in regards to its neighbors. Therefore, it is not always the case that links formed with a node that exhibit high frequency of movement will significantly impact the route discovery phase. Such impact also depends on the relative movement between nodes that form links. To give an illustration, we refer to Figure 3.2. If all nodes in this topology were moving with high frequency of ping pong with minimal relative movements among the nodes, the delay in route discovery would be minimal. On the other hand, high variability of such movement at high frequency will introduce high delays in the route discovery stage. In terms of relation to distance vector and during the route discovery phase, the main impact of node movement is delay, which in our opinion may, in specific cases and due to node frequency as well as topology composition, result in such variability that mainly jeopardize the whole routing process, as the route discovery phase may be delayed significantly for a distance-vector approach.

For the case of a link-state protocol such as OLSR, then route discovery is performed in a proactive way based upon the HELLO control messages and also based on the notion of *Multipoint Relay (MPR)*. This assists in reducing flooding on the network, in contrast to the original link-state routing approaches. OLSR is better suited for large, dense environments. Moreover, OLSR can tune the frequency of information exchange and thus provides, in principle, better support for node movement. In terms of the route discovery phase, the impact of node movement again relates to the parameters already discussed, namely: correlation of movement pattern to time (frequency and type of movement) as well as to node degree and network density. The main difference in comparison to AODV during this phase relates to the proactive behavior, which provides more stability when nodes move. Let us again consider Figure 3.2 and the provided (potential) paths. Again, we assume that nodes A and B exhibit some type of movement. The expected delay would most likely be lower, but the result would be the same in the sense that, again, the selected route would be the longest one independently of the fact that the movement type and frequency could imply that, after a small delay, the best route could indeed be the shortest one. In other words: none of these families currently includes a natural (metric-based) way to detect such minor variations and to ignore them. In terms of different multi-hop approaches, while with AODV the result may be a significant delay, with OLSR the delay may be smaller but the signaling overhead may significantly increase, depending on the type of movement, frequency of movement, as well as related to the position of the node(s) moving from an end-to-end path perspective.

The Impact of Node Mobility on The Route Maintenance Phase

Again considering the AODV perspective, we discuss the potential impact that node movement has during the route maintenance phase. A topology change may occur due to a temporary link break, or due to a permanent link break. For instance, if one node moves from a specific position to another, hence there is a link break, but the node returns to its original position in a few milliseconds, and this corresponds to a temporary link break. A temporary link break does not always imply discontinuity from a routing perspective, and this is highly related to the type and pattern of movement. For instance, if a node exhibits confined movement as discussed, the frequency of movement dictates whether or not such movement may result into a temporary link break, or a permanent link break. Being on-demand (reactive), upon even a temporary link break, AODV triggers signaling in order to deal with topology changes. It may even happen that, upon the detection of a temporary break, AODV triggers path re-computation and the result may simply be the path that was already established. This will increase the signaling overhead in a way that could be prevented, if the applied routing metric would be capable of "isolating" these situations, i.e., by making the routing protocol understand when a change is temporary, or permanent, or simply react for cases where changes are permanent. Assuming that the type of movement implies some frequency of returning to the original position, then in addition to the signaling overhead, there is the delay which is highly dependent on such frequency.

In regards to the impact on a link-state approach (e.g., OLSR) during the route maintenance phase, due to its proactive nature, OLSR will detect quicker the location of a topology change, and due to the flooding nature, it will, most likely, heal such failure quick. However, for the case of a temporary failure there is no detection capability. Both temporary and permanent topology changes will be dealt with as a change and hence require re-computation. Signaling overhead is associated with this. The corresponding delay will be lower for OLSR than for AODV. However, both families treat temporary and permanent topology changes as permanent, thus requiring path re-computation. Despite the fact that such changes may be insignificant, the relative cost (be it in terms of delay or in terms of signaling overhead) seems to impact both protocol families the same way. Therefore, one main aspect to tackle in order to make routing more sensitive to node mobility is to consider metrics that are capable of capturing some properties of such movement. In the next section, we describe a number of parameters and of metrics that can be used to achieve such goals.

3.1.3 Characterizing Mobility Parameters for Routing

Given that node mobility affects routing performance, there are a number of mobility parameters that aim to capture node mobility to make routing more sensitive to mobility. In this section, we provide a review of the existing mobility parameters to determine their sensitivity towards node mobility. A routing protocol robustness in the face of node mobility depends on the level of sensitivity of the mobility parameter(s) used. The parameters under study in this section are: link duration or lifetime, node degree stability, ratio of static nodes vs. moving nodes, average number of link breaks, and *pause time*.

Link Duration

Link duration (LD) is a parameter that is tightly related to the movement of nodes and is also, as of today, one of the parameters that is most popular in terms of tracking node mobility. By definition, link duration is associated to the period of time where two nodes are within the transmission range of each other. In other words, it is the time period that starts when two nodes move to the transmission range of each other and that ends when the signal strength perceived by the receiver node goes under a specific threshold [52][80][86].

Today's definition of LD only assimilates node mobility in regards to its relation to signal strength. It fails, however, in terms of sensitivity to movement patterns. For instance, the current LD does not capture the case where a node jumps between its original position and a second position with a frequency that is not significant in terms of the potential delay it causes. Such movement will trigger repeated re-computation, which brings in more delay than if such frequent hopping would simply be disregarded. As far as mobility patterns are concerned, LD captures link stability of nodes that do not reach their link break threshold. However, it cannot distinguish between a temporal and a permanent link break.

Pause Time

Pause time is the period of time that a node is stationary [81]. Khamayseh *et al.* used Pause Time to determine node mobility levels, with an assumption that the higher the Pause Time a node had, the more stable it was in terms of mobility, thereby developing more stable links to be used for routing [39]. Pause Time, as a mobility parameter, captures node stability in terms of mobility for nodes that are static. However, existence of temporal and spatial correlation allows formation of stable links among nodes portraying this feature. In other words, Pause time captures mobility partially only.

Average Number of Link Breaks

Another parameter that assists in tracking mobility dynamics is the *Average Number of Link Breaks (ALB)* estimated in a specific interval for a node i, ALB_i [52]. If node i experiences a high ALB, then through time it may be a node to avoid, if the goal is to provide robust paths. This implies that, although it is interesting due to the easy computation of such parameter, ALB

can only assist in integrating mobility-awareness in terms of the route discovery phase, given that it may assist in setting up more robust paths. However, as previously highlighted by Tran *et al.* in [79], this mobility parameter is node density dependent.

Node Degree Stability/Rate of Changing Neighbors

From a mobility perspective, a change in node degree means that there is node mobility. It may be node i moving, neighbors of node i leaving communication range of node i or new neighbors arrival. It should be noticed that, from our mobility analysis perspective, having nodes moving towards others is the same as having nodes simply joining or leaving a topology. Also, node degree is agnostic to mobility when an average number of nodes leaving is the same as the number of new neighbors. Hence node degreeper se is not an adequate mobility tracking parameter. However, if one considers the variation of the node degree through time, one may be able to infer some mobility properties. We name this parameter Node Degree Stability and refer to it in the next chapters as NDS_i.

Ratio of Static Vs. Mobile Nodes

The ratio of static vs. mobile nodes (or a ratio between them) in a network estimated through time, and for the perspective of a single node i is here defined to be an evolution of NDS_i, and a parameter that can be considered in order to partially capture mobility dynamics of a network. Through time, if the percentage of nodes moving is low in comparison to the static nodes, it is more likely to have more stable links. It is also relevant to be able to capture the dispersion (and not only the percentage) of such nodes in the network.

Discussion

Mobility parameters discussed so far capture node mobility but only partially. Out of the ones described, LD seems to be the most relevant to consider in regards to attempting to develop routing metrics that can assist in tracking mobility dynamics, in particular regarding node movement with patterns that exhibit some recurrent behavior (e.g., ping-pong movement). The remainder of the parameters are relevant and may be applied to assist parameters such as LD, in building more robust metrics. It is, however, our belief that LD requires a more thorough characterization

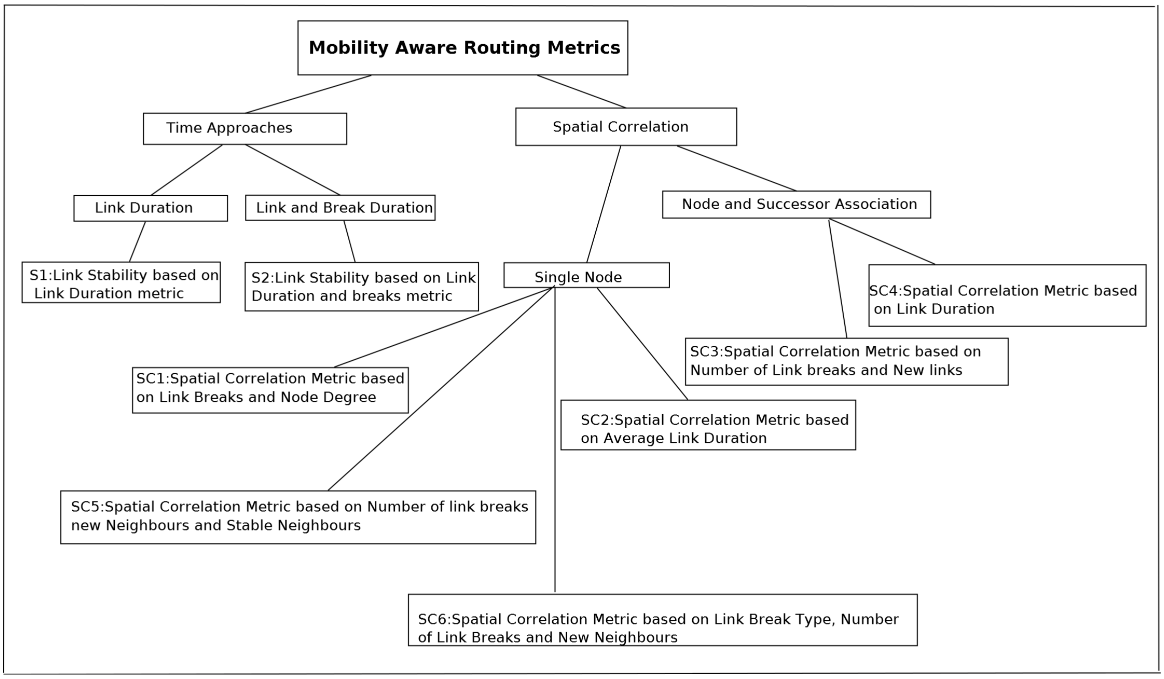


Figure 3.3: Mobility Aware Routing Metrics.

to be able to integrate routing metrics that are more sensitive to movement.

3.2 Mobility-aware Routing Metrics

In this section we discuss the routing metrics that were devised to aid in making routing more sensitive to node mobility. A number of mobility parameters have been used to capture different aspects of node mobility. For example, the *number of new neighbors,* $nn_t(i)$ has been used to capture the node mobility that results into nodes coming in each other communication range, while the parameter *link duration,* $ld_t(i,j)$ captures the stability of two nodes that remain in each other communication range for some time.

Our proposal contains two different sets of metrics: the first is time-based (i.e. based on link activities over time) and the second employs spatial correlation characteristic between a node and its neighbors and hence, we name this family as *"spatial correlation"*.

Figure 3.3 provides an illustration for the families of mobility-aware routing metrics that we have proposed. Concerning time-based approaches, the first metric devised, $s1$, considers a single parameter (link break duration) as the basis for routing sensitivity to movement. Then, $s2$, which considers both the link break duration and the number of link breaks, has been developed. In what concerns the spatial correlation metrics, we have considered different parameters, such as the node degree, link duration, changes in the neighborhood of a node (new neighbors vs. stable neighbors, for instance). For this set, we have then applied a single node view, and a perspective that takes into consideration both a node and its potential successor view.

In the spatial-correlation family we have devised several metrics, $sc1$ to $sc4$. $sc1$ employs the number of link breaks a node incurs against the node degree; metric $sc2$ is based on the link duration. Both metrics fall under the single node pespective sub-family. The two metrics that consider a node and its potential successor view are $sc3$ and $sc4$. Metric $sc3$ uses mobility parameters such as the number of link breaks and new links to capture node mobility variability, while $sc4$ is based on the link duration. In addition to sc1 and sc4, which have been validated and for which results are provided in chapter 5, our work has devised two additional metrics $sc5$ and $sc6$, which we address in the next section.

The set of variables and parameters that have been used in the metrics is explained in Table 3.1.

3.2.1 Time-based Routing Metric Family

This category of routing metrics employs link activities over a period of time, such as the number of link breaks incurred, to ascertain the stability of a node as a successor in terms of mobility. As mentioned above, nodes that portray high levels of link stability make better routing candidates, as they are not susceptible to high mobility variability that causes link breaks. Large volume of link breaks is an indication of low level of link stability, and nodes whose links portray such behavior should be avoided as successor nodes in a routing path. As far as user-centric routing scenarios are concerned, since nodes portray human mobility characteristics, high levels of link stability among nodes are expected for nodes that tend to spend long durations of time in each other's proximity (e.g. devices carried by classmates during a class section or workmates).

In order to assist in developing a cost associated to link stability, we have considered two different routing metrics associated to the notion of link break and duration, and to the relation of these two elements.

Table 3.1: Metric Parameter Description.

Parameter	**Meaning**	**Computation**
$ald_t(i)$	Average value of link duration for node i. This is the weighted average of $nd_t(i)$ link duration values	$\left(\frac{\sum_{j=0}^{nd_t(i)} ld_t(i,j)}{nd_t(i)} \right)$
$a_t(i,j)$	Constant of value 1, used in the computation of the parameter new neighbors.	$a_t(i,j)$ is a constant of value 1 signifying a valid link between node i and neighbor j at time t. $a_t(i,j) = 1$ when $ld_t(i,j) < t$ and $a_t(i,j) = 0$ when $ld_t(i,j) > t$
lb(i,j)	The duration of time for which the link between node i and node j is not active (is down), during monitoring time T.	$\sum_{t=0}^{T} lb_t(i,j)$, where T corresponds to the size in seconds of the selected time-window.
$lb_t(i,j)$	The duration of a link break between i and j, sampled at instant t.	$lb_t(i,j) = lb_{t-1}(i,j) + t$
ld$_t$ (i,j)	The duration of time for which the link between node i and j has been active, sampled at time t.	$ld_t(i,j) = ld_{t-1}(i,j) + t$
lf(i,j)	The duration for which the link between node i and node j is active during monitoring time T.	$\sum_{t=0}^{T} ld_t(i,j)$,
nb(i,j)	Number of link breaks incurred by node i due to the movement of either node i or neighbor j over monitoring time T.	$\sum_{t=0}^{T} nb_t(i,j)$, where T corresponds to the size in seconds of the selected time-window.
$nd_t(i)$	Node Degree of node i. Node degree is the number of valid neighbors of node i at time t.	Obtained via sampling at instant t.
$nlb_t(i)$	Number of link breaks incurred by node i during monitoring time T.	$\sum_{t=0}^{T} nlb_t(i,j)$ where $nlb_t(i,j)$ is the number of link breaks that node i incurrs with its neighbours in t time units
$nn_t(i)$	Subset of neighbors (nd) which are newly formed (i.e. less than t time units)	$\sum_{j=0}^{nd_t(i)} a_t(i,j)$
$no_t(i)$	Subset of neighbors (nd) which have been in existence for more than t time units	$nd_t(i)$ - $nn_t(i)$
$sld_t(i)$	Sum of all link durations, for all links of node i.	$\sum_{j=0}^{nd_t(i)} ld_t(i,j)$, t $\in [0,T]$

S1: Link Stability Based on Link Break Duration Routing Metric

The first embodiment s1 considering the perspective of node i and a link (i, j) is represented in Equation 3.1 [16]. $s1(i, j)$ comprises the ratio between the time a link is down, *lb(i,j),* and the link lifetime *lf(i,j),* for the duration that elapses between two consecutive breaks (refer to Table 4.1).

$$s1(i,j) = \frac{lb(i,j)}{lb(i,j) + lf(i,j)} \tag{3.1}$$

The ratio between the duration of all link breaks incurred by a node against the full duration of that link, from the perspective of node i, gives a measure of stability in the sense that the more prone a link is to break the lower is its stability. It is a simple metric, which should assist in prioritizing links over time, and in choosing the ones that have a lower $s1(i, j)$. s1 assists routing in distinguishing short-lived links, since the duration in which the link is in the broken state (*lb*(i,j)) will be large. As nodes move, new links are formed and others are broken, meaning that link stability can change with time. A good routing metric is one that captures the change in stability. A link break means that there is a change in the link stability. In our metric, link cost depends on the time that the link has been down; links that incur long breaks will not participate in routing in the presence of links that are stable. Link stability depends on the time that the link has been down and up.

Implicitly, the metric captures nodes that are in group mobility. It can differentiate links that are formed between two mobile groups whose propagation path differ. It can also capture stable nodes that are static. The metric has the capability to capture link stability from familiar nodes. With humans tending to have preferred location where they spend most of their time, the metric encourages routing using the nodes that spend long durations in each other communication ranges, and it also has the capability to learn from previous node's meeting. This allows nodes that tend to meet for long duration of time with some frequency to be used in routing.

S2: Link Stability Based on Link Break Duration and Number of Link Breaks

s2 [16] corresponds to a second proposal under time-based metrics, where in addition to the link break duration and the total link duration, we incorporate the number of link breaks, *nb(i,j)* as shown in equation 3.2.

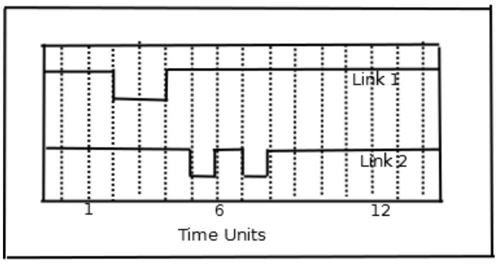


Figure 3.4: Link Activity Example.

$$s2(i,j) = \frac{lb(i,j) * nb(i,j)}{lb(i,j) + lf(i,j)} \tag{3.2}$$

$s2(i,j)$ takes into consideration the time period that a link is active, and also the number of breaks incurred with respect to a specific time window. In comparison to $s1(i,j)$, $s2(i,j)$ not only considers the percentage of time a link is active, but it also includes the frequency of breaks during that period. To provide a concrete example, let us consider two links *(i,1)* and *(i,2)*, with the same lifetime: *lf(i,1)* = *lf(i,2)* = 13 seconds. These 2 links experience also the same total link break duration, i.e., 2 seconds. As can be shown in figure 3.4, the frequency of breaks impacts differently the perceived stability. On the first link, the inactive time is derived from one single break, while for the second link, the total link break is the result of 2 link breaks. Assuming that we would apply *s1(i,j)*, both links would have the same s1; if we apply instead *s2(i,j)*, then 1 is chosen as a best successor in comparison to 2.

Computational Aspects

The family of time-based metrics relies on a single algorithm depicted in Alg. 3.1. Each node i periodically computes the metrics, independently of the routing mechanism in place. The computation is based on a time-window mechanism where each window is of size t seconds. This size can be best adjusted to the protocol where the metric is to be integrated. Active links are periodically monitored based on the usual node monitoring (OSI Layer 1 and OSI Layer 2) mechanisms. The routing adjacency matrix is consulted to capture the aspects concerning node neighborhood. Each time a new entry for a successor node is created, all parameters are set to 0. Once t seconds are reached, then *lf(i,j)* increases by t seconds. If instead, the link has been lost,

Algorithm 3.1 Time-based Metric Algorithm.

While t <=T
  every t seconds
    check adjacency matrix/neighbor table
    for each active j
      $lf(i,j) = lf\ (i,j) + \mathrm{t}$

    for each inactive j
      $lb(i,j) = lb(i,j) + \mathrm{t}$
      $nb(i,j) = nb(i,j) + 1$

At T seconds:
compute time-based metric

then $nb(i,j)$ is incremented, and $lb(i,j)$ is increased by t seconds. The metrics are then computed based on these updates.

3.2.2 Spatial Correlation-based Routing Metric Family

Spatial correlation-aware routing metrics work to capture node stability with its neighbors [18]. A node that has low or no mobility variability within its neighborhood can be considered "stable" from a movement perspective, and may be a good successor on routing paths. Routing metrics under this routing family can further be subdivided into two categories of node and successor association-based routing metric sub-family, and single node perspective-based routing metric sub-family. The node and successor association sub-family comprises routing metrics that also take into consideration successor correlation. This is to avoid a very stable node with respect to its neighbors from being a successor node, when it barely has a stable link with the current node, as this would create network partitions. We discuss in detail routing metrics devised under the two categories of node spatial correlation family.

Single Node Perspective-based Routing Metric Sub-Family

SC1: Spatial Correlation Routing Metric-based on Link Breaks and Node Degree
Our first metric, $sc1(i,j)$ [94] presented in Eq 3.3, employs the number of link breaks against the node degree. The rationale for this metric is that nodes that are stable in relation to mobility have lower or no link breaks as they maintain their respective neighbor set. If node i incurs a high number of link breaks globally, then this implies that the correlation to its neighbors is

not stable, i.e., either node i is frequently moving, or its neighborhood is subject to frequent topological changes. $sc1(i,j)$ [94] provides one possible way to measure the spatial correlation stability by considering, at instant t, the node degree that i holds and compare it with the number of link breaks that were incurred by the node in the prior monitoring interval.

Equation 3.3 shows the mathematical representation of this routing metric.

$$sc1(i,j) = \frac{nlb_t(i)+1}{nd_{t-1}(i)},\ t \in [0,T] \tag{3.3}$$

where t-1 represents the prior sampling instant.

For stable nodes (i.e., nodes with low levels of node neighborhood variability), nodes with high node degree are preferred. This is because nodes with high node degree have higher probability of a link break, as any of the neighbors can move away. The fact that the node is able to have high number of stable neighbors is considered to be more stable, in terms of mobility, compared to another node with a lower number of stable neighbors. The metric also takes into consideration this kind of node stability.

To better explain how $sc1$ can improve routing, let us consider the following example. Assume two nodes (c and d) with node degree 3 and 10 at time $t-1$; and at t, if both nodes incur no link breaks, node d is more stable than node c, since the possibility of incurring a link break is higher with 10 neighbors than 3. sc1 finds application in scenarios where nodes portray a random mobility. The increase in mobility variability will lead to more link breaks, and the metric captures the stable nodes with low or no link breaks.

SC2: Spatial Correlation Routing Metric Based on Average Link Duration The metric discussed in this section is $sc2(i,j)$ [94], represented in Equation 3.4, where j corresponds to a neighbor of node i; $ld_t(i,j)$corresponds to the link duration of the link (i,j). The rationale for this metric is as follows: a node is a better candidate for routing if its cost is lower or equal to the node's average link duration.

Nodes with a high *average link duration (ald)* may have some of their neighbors with low link durations. Using the average node link duration, nodes with high stability with their neighborhood are captured and, by comparing the average node link duration to that of an individual neighbor link duration, candidate routing nodes with unstable links are avoided. The metric encourages routing among nodes in stable groups: for example, a node that has relatively high number of new neighbors compared to the number of old stable neighbors will be avoided. The routing metric can capture the stability in scenarios such as a node on a bus with few or no new neighbors. The routing metric has the mathematical representation of 3.4:

$$sc2_t(i,j) = min\left(ald_t(i,j), ld_t(i,j)\right) \tag{3.4}$$

where $ald_t(i, j)$ is the average link duration that node i has with its neighbors, and $ld_t(i, j)$ is the link duration of node i and its neighbor j.

Node and Successor Association based Routing Metric Sub-Family

As illustrated in figure 3.3, concerning spatial correlation we have considered two different approaches: a single node perspective, and a node and successor association based perspective. This section addresses the latter perspective.

SC3: Node and Successor Association based on Link Breaks and New Links *sc3(i,j)* [18] integrates as parameters the number of new links formed, $nn_t(i)$, as well as prior link breaks, $nlb_t(i)$, monitored at specific instants in time, represented as $c'_t(i)$ in eq.3.5:

$$c'_t(i) = nlb_t(i) * nn_t(i) \tag{3.5}$$

where $nlb_t(i)$ is the number of link breaks a node i incurs, and $nn_t(i)$ is the number of new neighbors created with node i in a time window.

In $sc3$, we have considered an exponential moving average of $c_t(i)$ to smooth out unstable periods that have occurred a long time ago, via eq. 3.6 and the metric is as shown in eq 3.7:

$$c_t(i) = \alpha c'_t(i) + (1-\alpha)\, c_{t-1}(i) \tag{3.6}$$

$$sc3_t(i) = \frac{c_t(i)}{ld_t(i,j)} \tag{3.7}$$

where $c_t(i)$ is the spatial correlation for node i and $ld_t(i,j)$ is the link duration between node i and node j.

SC4: Successor Correlation based on Link Duration sc4, represented in eq. 3.8 [18], aims to capture spatial correlation properties between a node and its neighbors via the use of average link duration. The rationale behind *sc*4 is that a node with a high average link duration towards a stable set of neighbors makes a better routing candidate. The metric ignores potential "temporary" neighbors by penalizing successors that incur small link durations. The metric has a mathematical representation as shown in equation 3.8:

$$sc4_t(i) = ld_t(i,j) * ald_t(i) \tag{3.8}$$

Computational Aspects

The spatial-correlation metrics rely on the algorithm illustrated in Alg. 3.2. Each node i periodically computes the metrics, independently of the routing mechanism in place. The computation is based on a time-window mechanism based on a time instant t that can be adjusted to best suit the underlying protocol. Active links are periodically monitored based on the usual node mechanisms. The usual adjacency matrix is considered. Each time a new entry for a successor is created, parameter $nn_t(i)$ is incremented and the flag is set. Once t seconds are reached, then $ld_t(i,j)$ increases by t seconds. If instead the link has been lost, then $nlb_t(i,j)$ is incremented. The metrics are then computed based on these updates.

3.2.3 Non-validated, Mobility-aware Metrics

This section gives insight into metrics that have been devised and not fully validated in simulation due to time constraints. We believe that the two metrics can improve routing performance in dynamic environments by exploiting two additional mobility aspects of *number of old neighbors*

Algorithm 3.2 Space-based Routing Metric Algorithm.

Time-window T=T+t seconds
  check adjacency matrix/neighbor table
    for each active j
      $ld_t(i,j) = ld_t(i,j) + t$
      $nd_t(i) = \mathrm{nd}_t(\mathrm{i}) + 1$

      if j is a new neighbor (neighbor flag off)
        $nn_t(i) = nn_t(i) + 1$
        set neighbor flag on
      else $no_t(i) = no_t(i) + 1$

    for each inactive j
      $nb_t(i) = nb_t(i) + 1$

After matrix check:
    compute $ald_t(i)$
    compute spatial correlation metric

($no_t(i)$) and *link duration ($ld_t(i,j)$)* at the time of link break occurrence. The number of old neighbors of a node gives a level of stability a node has with its neighbors; a node where most of its neighbors are new is an indication of high level of mobility variability a node has with its neighbors. On the other hand, a node with more old neighbors shows some level of mobility correlation between a node and its neighbors. Link Duration of a node with its neighbor j at the time of break shows the level of loss of stability a node incurs when the node moves away. A node with high mobility variability will have low values of parameter link duration with its neighbors when it has little or no mobility correlation with them. On the other hand, if a stable node pair incurs a break, the value of the parameter will be high. This could be as a result of an end-user device acting as a node departing from its preferred location.

SC5: Spatial Correlation Routing Metric Based on Link Breaks and Neighbors $sc5$, represented in eq. 3.9, considers a possible combination of 3 different parameters, $no_t(i)$, $nlb_t(i)$ and $nn_t(i)$. A node with a high number of link breaks and/or new neighbors has high mobility variability with its neighbors, and choosing it as a successor is not a good option as it is more liable to link breaks. This metric also considers the number of old neighbors of a node. The benefit of having a large number of old neighbors is two-fold. The node has a high number of potential successor nodes, and it is also an indication of node stability in terms of mobility variability with its neighbors. Each neighbor is a potential source of a link break. Therefore, a node that has a high number of old neighbors, compared to another one with low number of old neighbors, if both nodes have no mobility variability with their neighbors, the one with more old neighbors has more stability than the latter.

Using an exponential moving average, changes in stability levels that a node incurs are taken into consideration, where nodes that remain stable for a long duration are preferred. A good routing metric is one capable of tracking these changes. Metric $sc5$ captures these changes by taking into consideration previous mobility variability. The metric finds applicability in dynamic environments where node mobility levels are expected to change from time to time. For example, an end-user device acting as a node carried by a human who propagates a path from home to work where it meets nodes with different mobility scenarios, ranging from very stable of an isolated stable home to highly unstable scenarios. The metric has a mathematical representation as shown in equation 3.9:

$$sc5_t(i) = \alpha sc5_t{}'(i) + (1-\alpha)\left(sc5\right)_{t-1}(i) \tag{3.9}$$

where sc5$'_t(i)$ is represented by eq 3.10:

$$sc5_t{}'(i) = log\left(\frac{nlb_t(i) * nn_t(i)}{no_t(i)}\right) \tag{3.10}$$

The rationale is that stable nodes have few or no neighborhood changes which are obtained from the three parameters.

SC6: ***Routing Metric Based on Link Breaks, Link Break Type and Neighbors*** $sc6$ considers the number of link breaks and the number of new neighbors as $sc3$ to obtain the level of stability a node has with its neighbor. The metric also employs link break differentiation to determine the extent of loss of spatial correlation a node suffers in case of a link break. Neighbors with short link duration are not as stable neighbors as compared to neighbors with long link duration. As such, a link break involving a neighbor with long link duration contributes more to the loss of stability of that node compared with short-lived neighbors. For example, consider node a, with two neighbors (b and c) with link duration 1 time units and 40 time units, respectively.

If node a loses both neighbors at the same time, loss of stability of node a is contributed more by neighbor c compared to neighbor b. Using the exponential moving average, changes in node stability are noted, through preferring nodes that have maintained their neighboring nodes for a long time (i.e., nodes with high spatial correlation). The metric has a mathematical representation as shown in equation 3.11:

$$sc6_t(i) = \alpha sc6_t{'}(i) + (1 - \alpha)\left(sc6\right)_{t-1}(i) \tag{3.11}$$

where sc6$'_t(i)$ is represented by eq 3.12:

$$sc6_t{'}(\mathrm{i}) = (nlb_t(i) * log(sld_t(i)) * nn_t(i)) \tag{3.12}$$

The parameter $sld_t(i)$ allows the metric to capture the stability loss incurred by nodes through loss of neighbors that greatly contribute to the node stability. It may happen that a node leaves from one location where there are stable neighbors or the neighbors leave. The metric finds application is areas where stable groups are desintegrated, for example, nodes leaving preferred locations or nodes on a bus reaching its destination which result in nodes losing stable neighbors. The rationale is that stable nodes should be chosen as successors, and that nodes that lose their stability should be avoided as successors on routing paths.

3.3 Discussion

As discussed in Chapter 2, human mobility is characterized by patterns that exhibit statistically some level of predictability and preferred locations, where humans tend to spend some time. In this section, we discuss the scenarios where our metrics are expected to perform best.

The time-based metrics are expected to capture these stable or periodic neighbors and use them for routing when they meet. In case of unstable links that are formed among these nodes, metric $s2$ goes further to avoid nodes that incur link breaks. Node mobility variability can occur from time to time.

A node can have stable neighbors at one point in time and have none in the next instant. We give an example of a device carried by an individual commuting from home to workplace. At home, the device will have stable neighbors with other family member devices, as he commutes to his workplace, the device can have high mobility variability with other devices at meeting places, such as bus and metro stations due to his mobility and other people's. If he catches a train, his device will have high level of spatial correlation due to low relative velocities among devices on the train. The suitability of such a device as a successor node varies from time to time. Our metric $sc5$ captures these changes by taking into consideration previous mobility variability parameters $nlb_t(i)$, $no_t(i)$ and $nn_t(i)$.

Some scenarios in human mobility may appear to be random, where there are high levels of variability in movement patterns at the time, for example in meeting places such as shopping malls. Metric $sc1$ captures such variability by taking into consideration link breaks for a specified node degree. Metric $sc3$ goes further to capture node mobility that results into link formation too.

Nodes may exist in groups for both short and long periods of time. Metrics $sc2$ and $sc4$ employ the link duration parameter to determine the suitability of the node as a successor. In such scenarios, the metrics will capture stable nodes that maintain their neighbor set for a long period of time. Metric $sc4$ goes further to consider the successor correlation.

3.4 Summary

This chapter provided a discussion on when node mobility may become significant to affect multi-hop routing. Based on this, different aspects of mobility were discussed, such as: link length, node distance and node mobility patterns. We provided an analysis of how different node mobility characteristics affect the routing procedures of route discovery and maintenance. Given that it is evident that mobility affects routing, we reviewed some of the mobility parameters used to capture node mobility. These parameters are aimed at increasing routing sensitivity to node mobility. Their ability to capture node movements determines how robust routing becomes in the face of node mobility.

This chapter has dealt also with the mathematical formulation of two sets of metrics, one set that relies on the time to attempt to capture link stability, while the other set relies on parameters that allow a node to capture aspects concerning its spatial correlation towards its neighbors. Within the context of time-based approaches, we have selected $s1$ and $s2$ metrics, respectively provided in Eq 3.1 and 3.2, as metrics that can assist multi-hop routing in becoming more sensitive to node movement. In case of unstable links, metric $s2$ provides finer granularity in the sense that it can assist in penalizing links prone to a significant number of link breaks.

Then, in regards to spatial correlation, we have presented 2 metrics, $sc3$ (cf. Eq 3.7) and $sc4$ (cf eq 3.8), that consider node to successor association while $sc1$ (cf. Eq 3.3) and $sc2$ (c f. Eq 3.4) consider single node perspective. These four metrics shall be further explored in terms of implementation and validation aspects in the next chapter. Moreover, we have further explored 2 new metrics, $sc5$ and $sc6$ for which no validation could be carried out. Our hypothesis is that, by increasing the mobility capturing perspective, these metrics should be able to increase routing sensitivity to node mobility.

Chapter 4

Routing Metrics Validation and Results Analysis

4.1 Introduction

This chapter deals with the integration and the validation of metrics $s1$, $s2$, $sc1$, $sc2$, $sc3$ and $sc4$ into multi-hop routing protocols. As representative examples of multi-hop routing we have chosen OLSR and AODV. The validation has been carried out with discrete event simulations, based on ns2 [110]. The chapter starts by the description of the metrics implementation in AODV and OLSR, followed by the validation of the metrics, their results and performance analysis.

4.2 Mobility-aware Routing Metrics Specification Aspects

This section describes the implementation in ns2 of the proposed metrics using AODV and OLSR [104]. The proposed metrics are routing protocol independent as they are independently computed periodically at a node, as explained in the algorithms 3.1 and 3.2. We provide the corresponding parameter names used in AODV and OLSR implementation in table 4.1.

4.2.1 Routing Metrics in AODV

The integration of the different metrics in AODV is performed in two different moments. First, during setup, the different parameters are acquired via the exchange of HELLO messages, which

Table 4.1: Implementation Parameter Correlation for Metrics.

Metric Parameter	Corresponding Parameter in AODV Implementation	Corresponding Parameter in OLSR Implementation
$ald_t(i)$	node_duration	node_average_link_duration_
$lb(i,j)$	alh_total_link_break_duration	total_link_break_duration_
$lb_t(i,j)$	break_duration	lateast_link_break_duration_
$ld_t(i,j)$	nb_link_duration	link_duration_
$lf(i,j)$	alh_link_lifetime_duration	link_lifetime_
$nb(i,j)$	alh_number_link_breaks	number_of_link_breaks_
$nd_t(i)$	node_degree	node_degree_
$nlb_t(i)$	number_link_breaks	number_of_link_breaks_
$nn_t(i)$	number_new_links	number_of_new_neighbors_

allow the node to infer aspects such as link breaks, etc. Then, during path computation, by relying on RREQ and RREPs, to carry and to update the computed mobility-aware costs. In terms of the two family of metrics, what differs is the way that parameters are acquired. The path computation process is similar for the different metrics family, as explained in the following sections.

Parameter Acquisition and Mobility Cost Computation of Time-based Routing Metrics in AODV

For time-based routing parameter acquisition and metric computation, nodes monitor link activities with their respective neighbors to determine node suitability as a successor. The link activities in terms of number of link breaks and link break durations are obtained through analysis of the HELLO messages periodically sent by AODV nodes. Each node monitors link activities with its neighbors to obtain parameters used to compute the routing metric.

Below we explain the procedure to obtain the different metric parameters used in corroboration with a flowchart in figure 4.1.

The computation of the different parameters is processed in background. When a node i receives a HELLO message from one of its neighbors j (1), node i first checks if j is a new neighbor (2), by verifying in the adjacency matrix if a new node exists (3). If so, node i creates a new entry for node j (4). The entry is a tuple composed as $<j$; *lb(i,j); nb(i,j)*; link state; T; update_ time; break_time, lb_t(i,j) or break_duration $>$. All of the parameters are explained

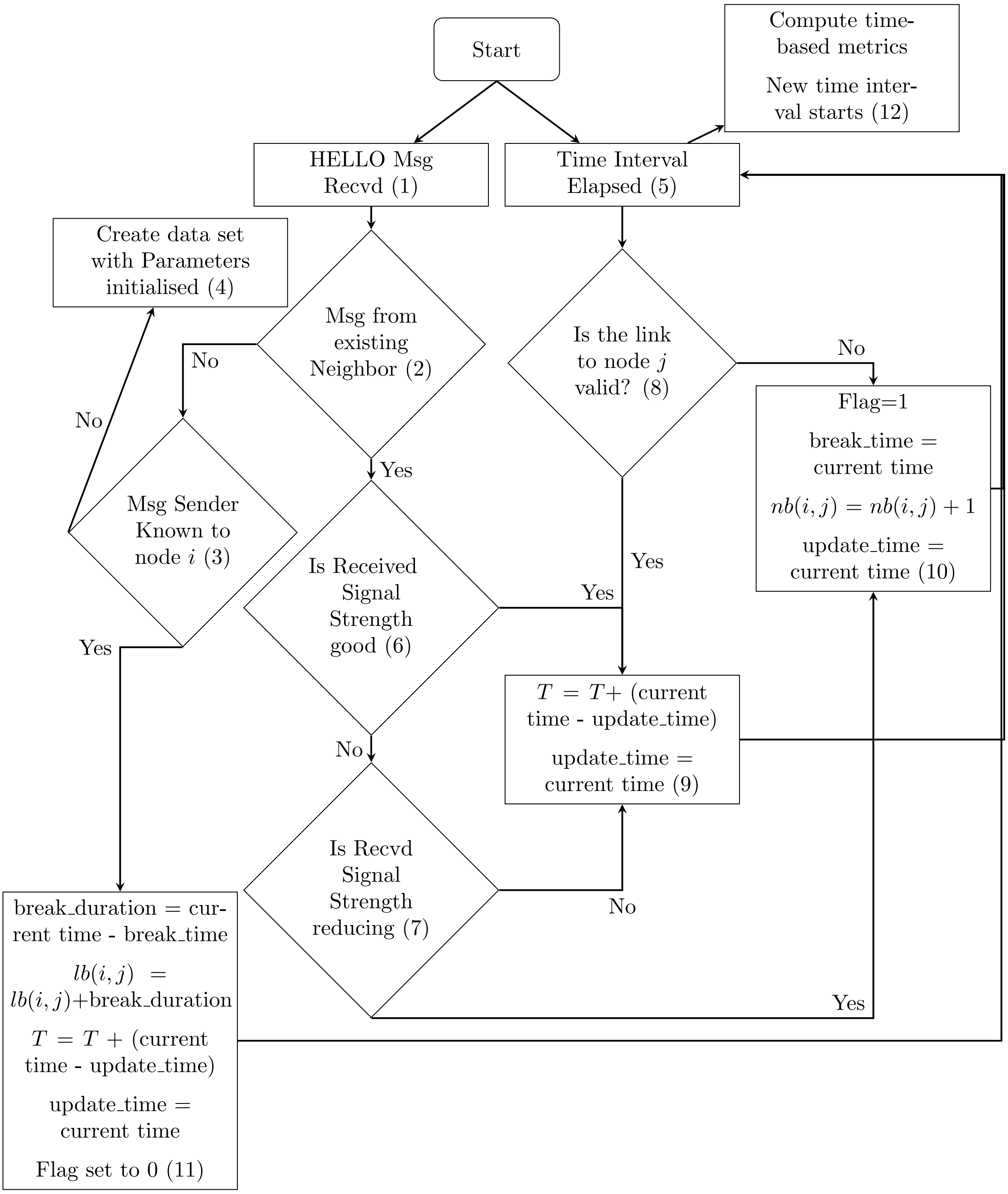


Figure 4.1: Time-based Metric Parameter Acquisition and Metric Computation in AODV.

in Table 3.1. Update_time shows the last time the tuple parameters were updated, and break time shows the time at which the last link break was noted. Using the break_time and the update_time, the link to node j is noted to be active again, and the parameter break_duration is obtained to show the duration of the latest link break. Lastly, T is the monitoring time equivalent to *(lb(i,j) + lf(i,j))*.

Parameter Acquisition and Mobility Cost Computation of Spatial correlation-based Routing Metrics in AODV

In case the entry already exists, the tuple is updated (11) as follows: $lb_t(i,j)$ and $nb_t(i,j)$ are computed*;* T is updated; update_time is set to current time and the flag is set to 0. For subsequent HELLO messages coming from node *j*, the received signal strength is checked (6) and, if it is good (i.e. above threshold), T is incremented and update_time is updated to current time (9). If the received signal strength is not good and is noted to be reducing by monitoring received HELLO messages (7), the flag is set, *break_* time is set to current time, *nb(i,j)* is incremented by 1 and update_time is set to the current time *(10)*. This also applies to expired neighbors (8) which have not sent HELLO messages in 6 seconds. In case HELLO messages are not received for a long period of time (in AODV, 3 missed HELLOS which by default correspond to 6 seconds), AODV deletes all expired neighbors. This is a periodic process, and in such case, before expiration (8) the neighbor entries are updated accordingly (10). The metric is computed thereafter (12).

To acquire parameter values for metric computations, the spatial correlation-based metric family also relies on HELLO messages as explained under time-based routing metric parameter acquisition, this time in corroboration with the flowchart shown in figure 4.2. We have introduced two flags for neighbor status: *nb_ link_ status* flag for old and new neighbors, and *nb_ link_ break_ flag* for link status whether active or inactive. To compute parameter $ald_t(i)$*,* an intermediate parameter *sum_* $ld_t(i)$ is updated with the sum of the updated values $ld_t(i,j)$ before an average $(ald_t(i))$ is computed. Periodically, nodes neighbors are checked for validity (i.e not expired neighbors) and are deleted if they are expired according to AODV operation. In case of expiry (5), or received HELLO message with low signal strength (2), $nlb_t(i)$ of node i is incremented and the *nb_ link_ break* flag is set to 1 (3). If the link to node j is still valid, parameter $nd_t(i)$, $ld_t(i,j)$ and *sum_* $ld_t(i)$ for node i are incremented (6). Also if the neighbor is new (7), $nn_t(i)$ is incremented and *nb_ link_ status* flag is set to 0 (8). Then, the parameter

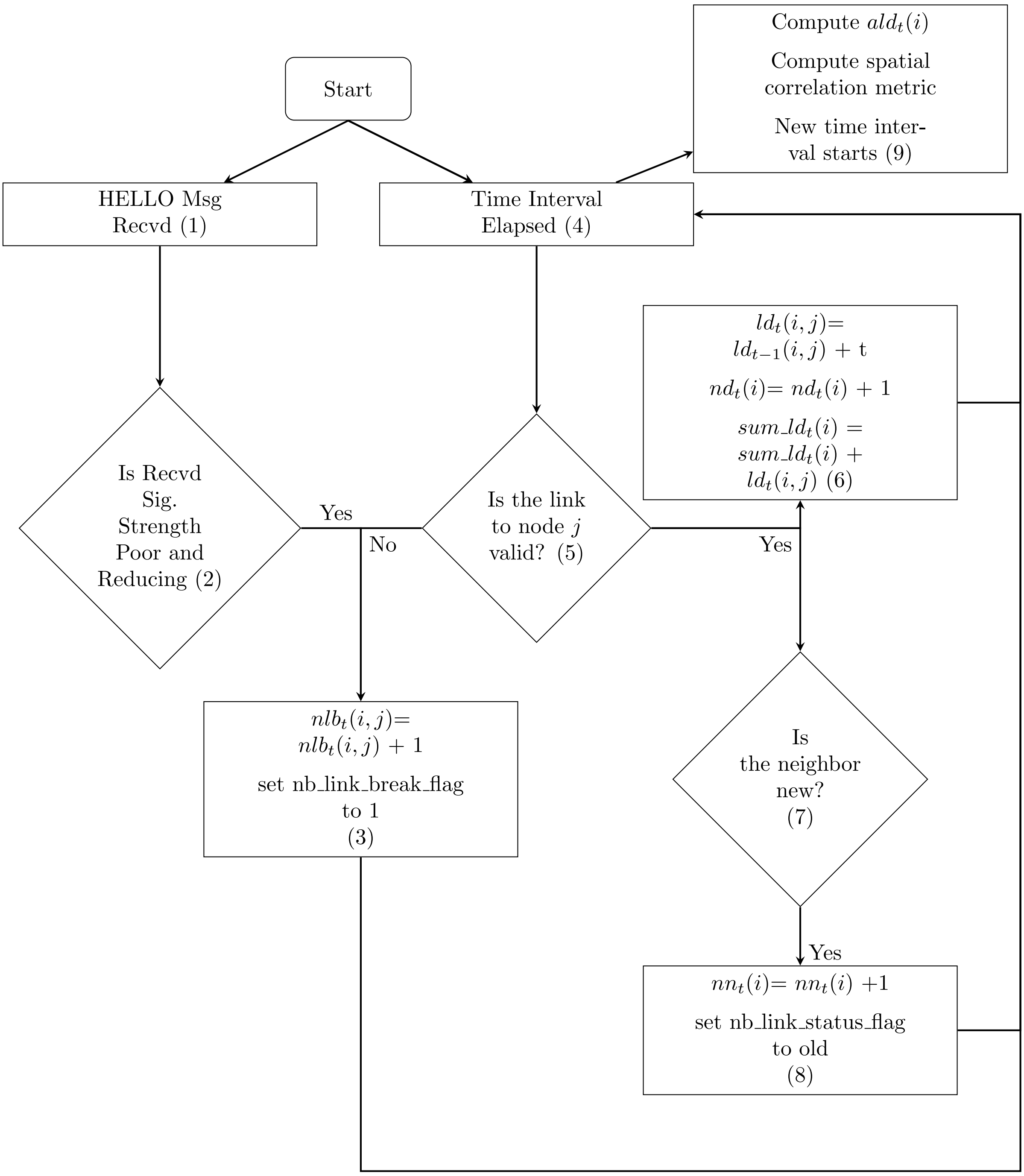


Figure 4.2: Spatial Correlation based Metric Parameter Acquisition and Metric Computation in AODV.

$ald_t(i)$ and the metric are computed (12).

Mobility Aware Routing using AODV

To make routing using AODV mobility-aware, path computations should take into consideration the metric values computed. As such control packets of Route Request (RREQ) and Route Reply (RREP) carry mobility costs as routes are discovered. We explain below how the route discovery and path computations are mobility-aware with the help of a flowchart 4.3.

When a node wants to send data (1) to a destination with no valid route, it broadcasts a RREQ (3) and the RREQ at the source has mobility cost (minimum) of 1. When a node receives a RREQ (4), if the node receives its own request (5), it discards it (6). For other requests received, the node updates the value of mobility cost to that carried in the RREQ. If a node has a valid route to a destination (7), it sends the RREP (8). Otherwise, if the request is the first one received for unique source node ID and RREQ ID, it is cached at the node to set a benchmark for mobility cost for RREQ received (11) and reverse route to the previous node updated or created. Subsequent requests received are discarded (6) if the mobility cost after the update of the RREQ with the new value is higher than the one cached; otherwise, they are cached and new benchmark mobility costs are set. If the node is a destination node (10), for the first received RREQ, a RREP control message is sent back to the source node updated with the total mobility costs of the propagated path (8). If the destination receives a subsequent RREQ from the same source and same RREQ ID but with better mobility cost, after updating it with the node mobility cost, another RREP is sent to the source node. Otherwise, the other RREQs are discarded. If an intermediate node has a fresh route, the mobility cost from the route and RREQ are added to form the new route path cost, and a RREP control message is sent to the source node. If a node is an intermediate node and does not have a path to the destination, it broadcasts the RREQ.

When the node receives a RREP (11), for a source node (12), if the RREP if the best or the first one (13), it updates the route and sends data (16); otherwise, it discards the RREP. In case of intermediate node receiving an RREP, it updates the route entry and unicasts a RREP (15).

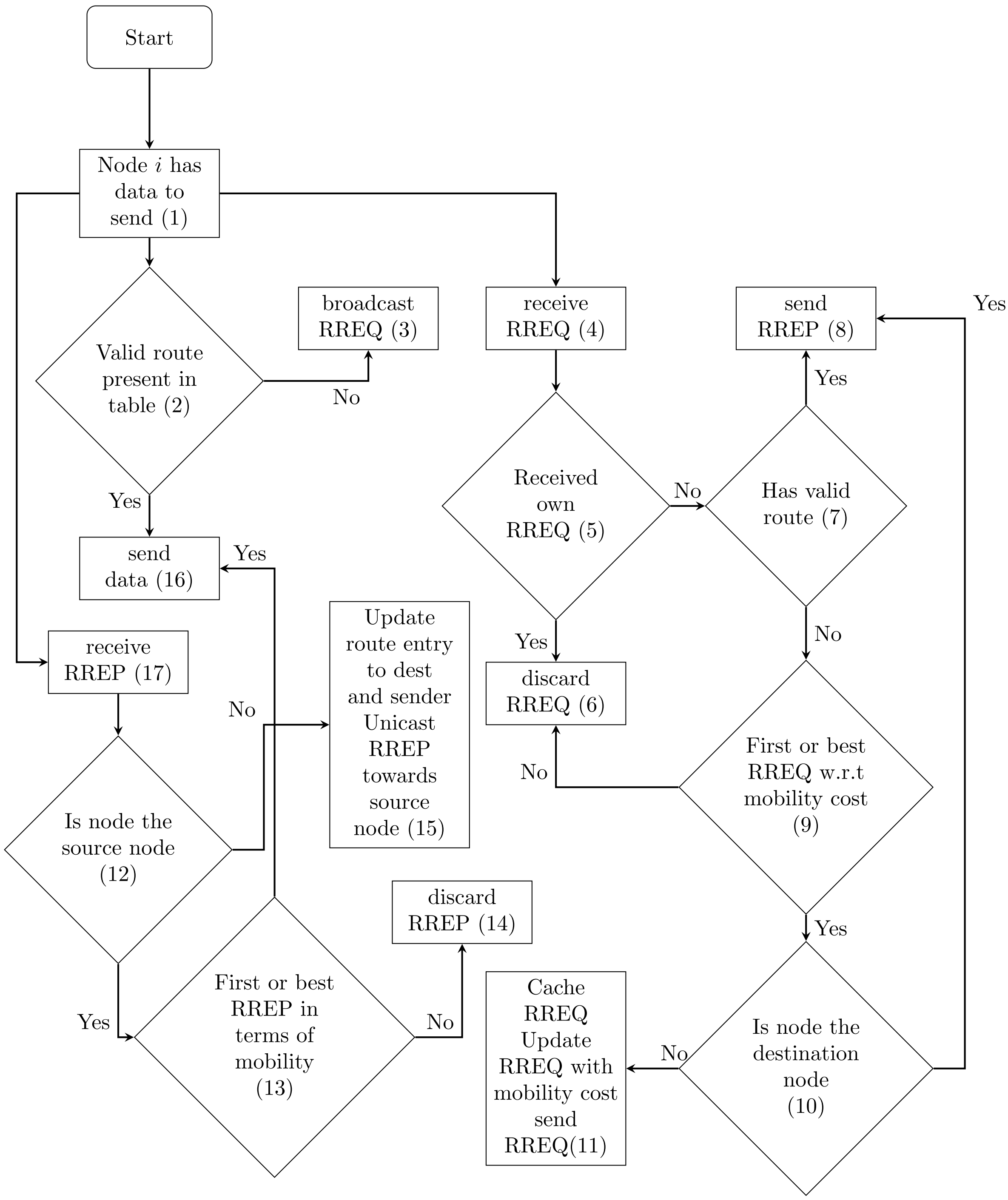


Figure 4.3: Mobility Aware routing in AODV.

4.2.2 Routing Metrics in OLSR

Parameter Acquisition and Mobility Cost Computation of Time-based Routing Metrics in OLSR

This section details the procedures to acquire the parameter values used inthe metric calculations in the Time-based routing family using OLSR. The parameters used in the calculations are: *nb(i,j)*, *lb(i,j)* and *T*. We have other parameters used to aid in computing and these are: link_status, latest_link_break_duration_ and time_. To help keep track of the changes in node neighbors' link activities, a data set on every node is created when a new neighbor is formed and is herein referred to as Link_Mobility set. The composition of the Link mobility set tuple is the following: node *j* identifier, *nb(i,j), lb(i,j),* time_, link_status, latest_link_break_duration_, and *T*. The parameter latest_link_break_duration_ is used for updating *lb(i,j).* The parameter *time_* is used for time-stamping and for the calculation of the *latest_link_break_duration_,* and the flag *link_status* indicates whether the link is active or not.

OLSR uses link sensing procedure to learn its neighbors using the exchange of HELLO messages.

Figure 4.4 shows a flowchart of the procedure we have used to capture different parameter values. When a HELLO message is received (1), the message is checked if it is from existing neighbors (2). If the sender of the message has not been a valid neighbor before (i.e. does not have a link mobility tuple in place (3)), then a tuple is created with initialized values of the parameters (4). Otherwise, it is considered to be a returning neighbor with parameters updated as in (5) with *lb(i,j)* and *T* being incremented. In case the HELLO message is from an existing neighbor, if the received signal strength is good, above the threshold (12), the parameters *T* and update time are updated (9). In case the received signal strength is reducing below the threshold for subsequent HELLO messages (10) or the neighbor is expired (7), the flag is raised and the parameter *nb(i,j)* is updated (8). At the expiration of the time interval (11), the metric is computed.

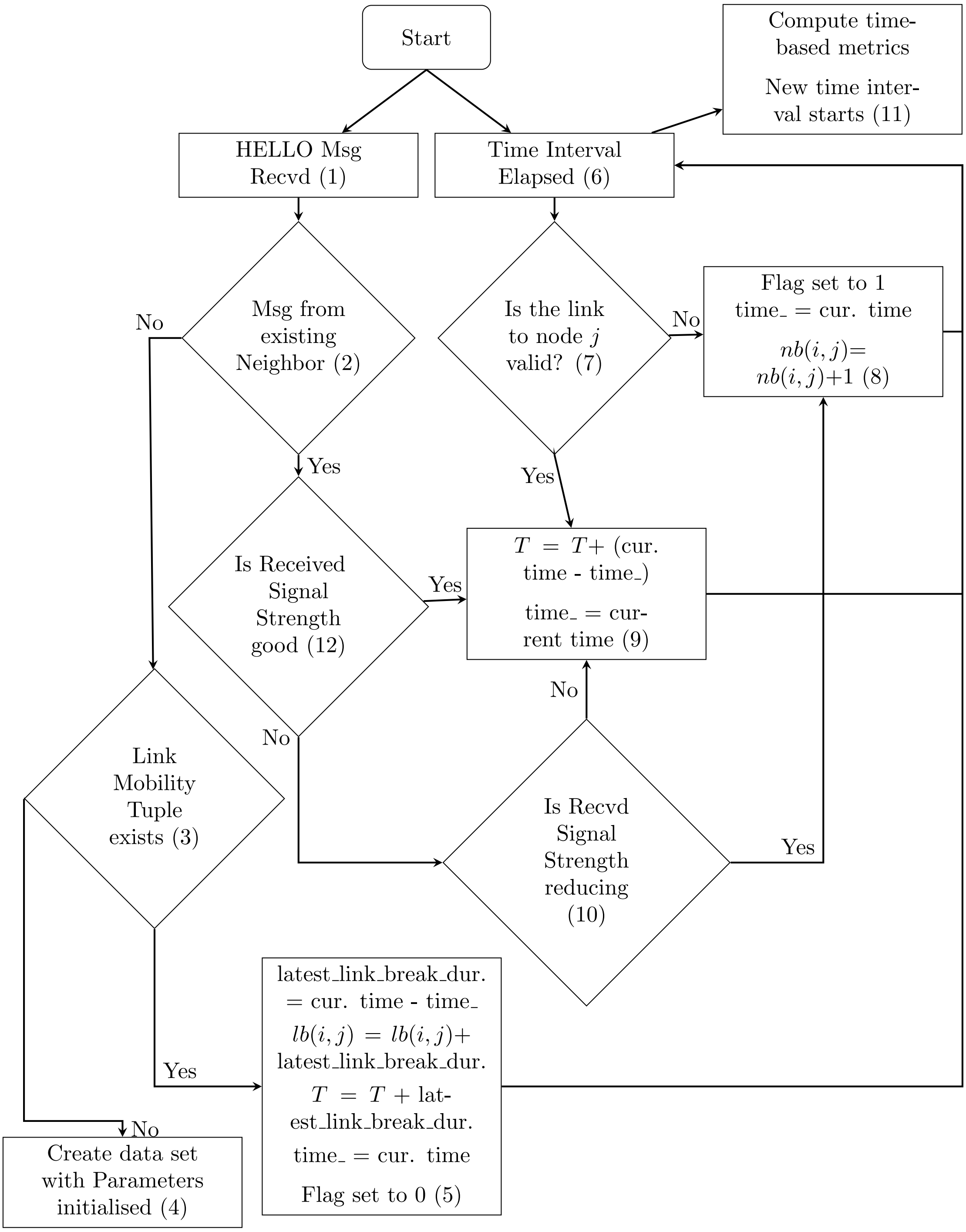


Figure 4.4: Time-based Parameter Acquisition and Metric Computation in OLSR.

Parameter Acquisition and Mobility Cost Computation of Spatial Correlation-based Routing Metrics in OLSR

Each node maintains a node mobility set that keeps mobility information from a node's perspective. The node mobility tuple comprises parameters, that aid in metric computation, and these are: $nd_t(i)$, $ld_t(i,j)$, $nlb_t(i)$ and $ald_t(i)$.

Figure 4.5 shows the flowchart describing parameter acquisition for the node spatial correlation family of metrics in OLSR. When a HELLO message is received (1), the message is checked if it is from an existing neighbor (2), and if not, then parameters $nn_t(i,j)$ and $nd_t(i)$ are incremented, and also an L_mobility tuple comprising node j identifier, status_flag and parameter $ld_t(i,j)$, cost is created (3). For neighbors whose HELLO messages are increasingly having low received signal strength (4) or expired neighbors (8), the links are considered broken and parameter $nlb_t(i)$ is incremented while $nd_t(i)$ is decreased; the flag is also set ((6). For valid neighbors, parameter $ld_t(i,j)$ is incremented for the corresponding L_mobility_tuple (5), and the parameter node_duration is computed. After the expiration of the time interval, $ald_t(i)$ and the proposed metrics are computed, and then the corresponding link mobility and link tuples are updated with the computed mobility cost of the metric (9); finally, parameter $nlb_t(i)$ is then initialized.

Node Neighborhood and MPR Selection

Each node in OLSR keeps a neighbor, 2-hop neighbors and MPR sets with the set members as described in *Internet Engineering Task Force (IETF)* draft [111]. To every neighbor set, neighbor mobility costs are calculated from the link set of the local node. Likewise, 2-hop neighbors are also updated with mobility costs to indicate the best known value of the mobility cost on the link from the node and its 2-hop neighbor. A database of neighbors selected as MPR is also maintained at the node, and MPR selection is performed as outlined in IETF draft [111] but using mobility costs.

HELLO Message Processing

The HELLO message generated by a node includes a link set, a neighbor set and an MPR set. These sets have been modified to include mobility costs. The implementation still relies on IETF draft [111] with mobility costs being added to the message. When a HELLO message is received,

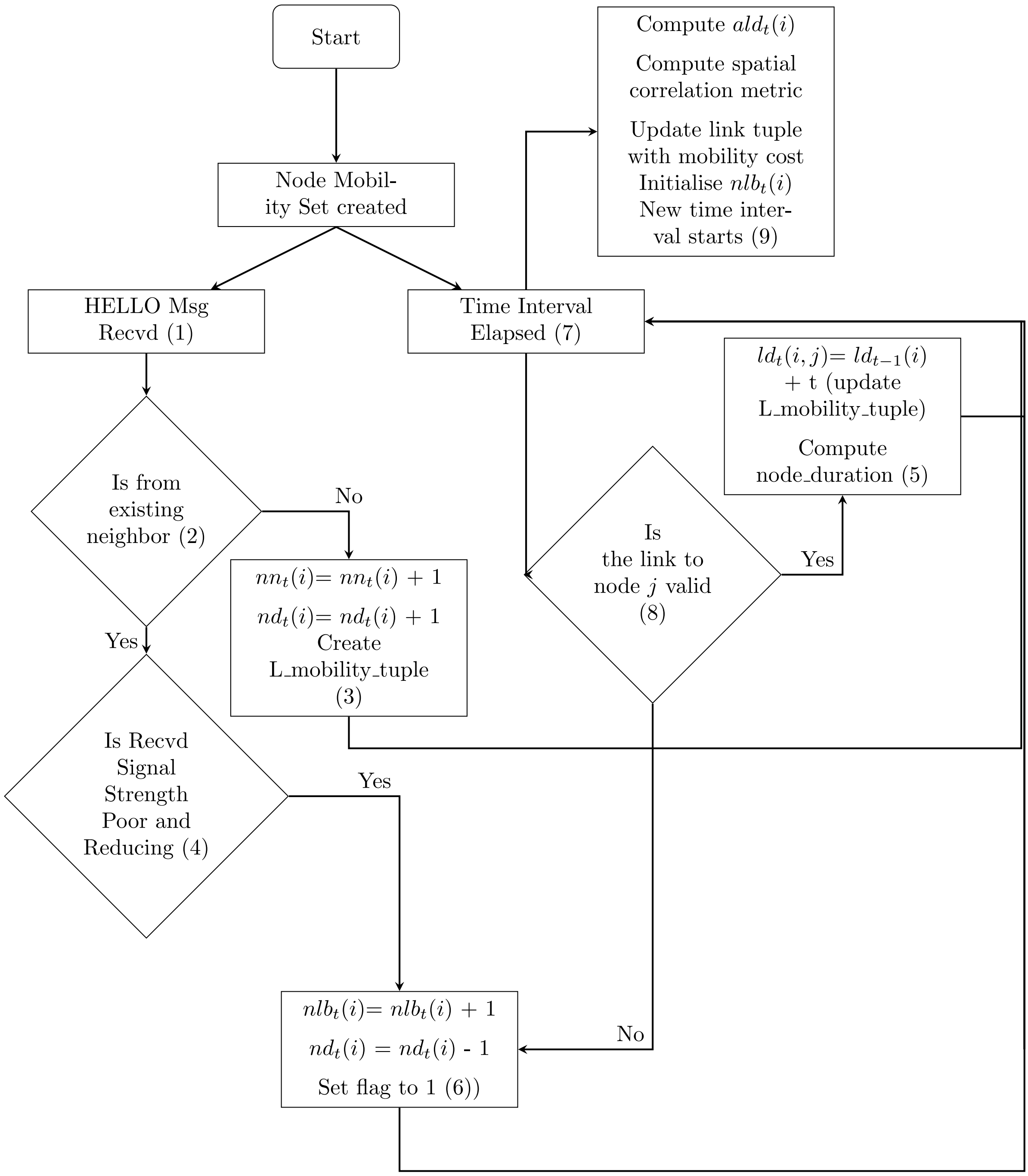


Figure 4.5: Spatial Correlation-based Metric Parameter Acquisition and Metric Computation in OLSR.

the receiving node updates the information received with regards to the sender, which includes the mobility costs. While the link set keeps the mobility condition of the links to the neighbors, neighbors keep the best mobility cost of the available neighbors.

Topology Control Messages and Routing Table Calculations

Each node maintains topological information. To each topological entry, a mobility cost is updated as in the procedure in [111][112]. A node selected as MPR node declares nodes that have selected it as an MPR with corresponding mobility costs, since MPR selection is mobility-aware. The TC messages dissemination helps in building a routing table, as MPR selector sets are made known to other nodes as described in the IETF draft [111].

4.3 Metric Validation

In a quest to explore how human mobility patterns affect routing and to understand the robustness of the proposed routing metrics, a set of simulation scenarios have been developed and tested.

A review of existing open source testbeds was done. Among the ones considered was *Open-Access Research Testbed for Next-Generation Wireless Networks (ORBIT)* [108]. However, it was noted that mobility characteristics of nodes in the testbed, when present, did not emulate human mobility characteristics. The second validation option that was made, due to our inability to use testbed, was to use simulations with human mobility traces to provide node mobility patterns in topologies. For this, a review on data sets consisting of human mobility traces was carried out. Among those taken into consideration were *North Carolina State University, (NCSU)* and New York traces obtained using *global positioning system, (GPS)* from Crawdad [105], a community resource for archiving wireless data at Dartmouth. The obtained results using these traces were inconclusive since routing metrics behaved very similarly due to high levels of network partitions that existed in the topologies, leading to having no or limited available paths for routing. With this, our next option was to use synthetic human mobility traces that would be obtained from mobility models that mimic human mobility characteristics.

We considered the parameters in ns2.34 to mimic Wireless Fidelity (wi-fi) 802.11b, being the parameters shown in Table 4.2. We varied several parameters in order to generate adequate scenarios. We used 6 mobility scenarios each consisting of 20 nodes and covering an area of 1000

Table 4.2: Summary of Simulation Parameters.

Parameter	**Value**
Simulation Time	500 sec
Simulation Area	1000X 1000 m^2
Transmission Power	2.8 x 10^{-5}
Propagation Model	TwoRayGround
Number of nodes	20
Packet Size	512

x 1000 m2 summarized in tables 4.3, 4.4, 4.5, 4.6 and 4.7. The first two scenarios (scenario I and scenario II) are RWP scenarios with maximum pause duration of 60 seconds. Scenario I (SCN I) and scenario II (SCN II) have nodes moving with speed ranging from 0.5 to 5m/s and 6 to 20m/s, respectively. The second set of node mobility scenarios are Community Mobility Model (CMM) scenarios (i.e. scenario III and scenario IV). The CMM mobility scenarios comprise two rows and three columns to form different attraction points. Like in RWP scenarios, node speed ranges are between 0.5 and 5m/s for scenario III (SCN III), and between 6 and 20m/s for scenario IV (SCN IV). The last two scenarios (SCN V and SCN VI) are Self-similar Least-Action Walk (SLAW) scenarios with 10 destination locations, nodes with pause duration ranging from 10 to 60 seconds with a Alpha value of 0.3. SCN V and SCN VI have a Hurst parameter of 0.3 and 0.7, respectively.

Table 4.3: RandomWay Point Scenarios (Scenario I and II).

	Scenario I	Scenario II
Area	1000 x $1000m^2$	1000 x $1000m^2$
Speed Range	0.5 - 5m/s	6 - 20m/s
Max Pause Duration	60s	60s

Table 4.4: CMM Scenarios (Scenarios III and IV).

	Scenario III	Scenario IV
Area	1000 x $1000m^2$	1000 x $1000m^2$
Speed Range	0.5 - 5m/s	6 - 20m/s
No. of Rows	2	2
No. of Columns	3	3

Table 4.5: SLAW Scenarios (Scenarios V and VI).

	Scenario V	Scenario VI
Area	1000 x 1000m^2	1000 x 1000m^2
No. of Destinations	10	10
Min Pause Time	10	10
Max Pause Time	60	60
Hurst Parameter	0.3	0.7
Dist Alpha	3	3

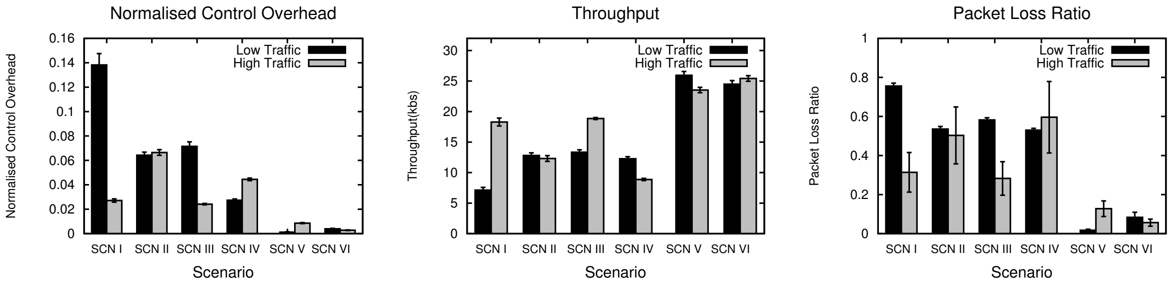
Table 4.6: Traffic Load Parameters-CBR.

	Low Traffic Load	High Traffic Load
No. of Flows	2	8
Traffic Type	CBR	CBR
Rate	2.4kbs & 128kbs	2.4kbs & 128kbs
Packet Size	512	512

Table 4.7: Traffic Load Parameters-VBR.

	Low Traffic Load	High Traffic Load
No. of Flows	2	8
Traffic Type	VBR	VBR
Rate	32kbs	32kbs
Burst Time	500ms	500ms
idle_time	100ms	100ms
Packet Size	512	512

Traffic scenarios used are *Constant Bit Rate (CBR)* and *Variable Bit Rate (VBR)* both obtained from traffic generators integrated in ns2. Tables 4.3 to 4.5 show the different mobility scenario characteristics obtained from the three mobility models, used in our simulations. Tables 4.6 and 4.7 show traffic scenario characteristics used for CBR and VBR traffic types. Simulations have been set to last 500 seconds to fully attain mobility characteristics of the model. All simulations have been run several times, with different random seeds, and computed within a 95% confidence interval. The proposed routing metrics have been implemented ns2 version 2.34 [110] as part of two different modules: AODV module [7] and the OLSR module. The simulator was chosen for its stability, wide use and support for multi-hop routing in ad-hoc network environments. The validation has considered native AODV and native OLSR against AODV and OLSR running our



(a) Normalized Control Overhead. (b) Achieved Throughput. (c) Packet Loss Ratio.

Figure 4.6: Impact of Mobility Models in AODV.

proposed metrics.

Our measurement of performance is based on performance indicators of achieved throughput, packet loss ratio, number of path re-computation and signaling overhead. GNU-awk [106] scripts are used to obtain performance indicator parameters, with the obtained results being plotted using GNUPlot 4.4 [107].

4.4 Results and Performance

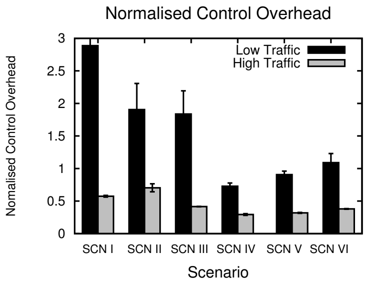
In this section we discuss the results of the experiments carried out to analyse the performance of the proposed routing metrics. Before presenting the performance analysis of the metrics themselves, the next section goes over a performance analysis which we have performed, concerning the impact that different mobility models have on AODV and OLSR.

4.4.1 Impact of Mobility on Routing

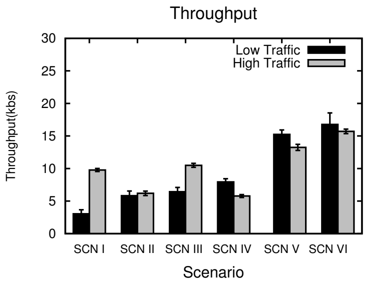
The results presented in this section have been obtained via ns2 simulations carried out to understand the impact that different mobility models have in the performance of multi-hop routing approaches. We have selected three representative mobility models: RWP; CMM; and SLAW.

AODV Impact

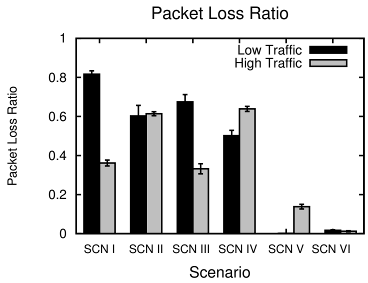
Figure 4.6a) depicts the results of control overhead for scenarios involving the three mobility models. Across all scenarios there is a significant difference in the performance, which seems to be worse when applying RWP (SCNI, SCNII). This is because in RWP scenarios, when nodes



(a) Normalized Control Overhead.



(b) Achieved Throughput.



(c) Packet Loss Ratio.

Figure 4.7: Impact of Mobility Models in OLSR.

reach their respective destinations, they pause and change direction and speed randomly to the next destination, which leads to unexpected breaks in paths well established. This is a somewhat artificial feature of this model, which significantly affects the results in experiments with AODV. We now look into throughput results (Figure 4.6 b), where the impact of RWP seems to be higher than the one of SLAW. The reason for this different impact is that SLAW generates routes based on waypoints. As such, nodes tend to frequently visit some of the provided waypoints. In contrast, by applying RWP, there is more variability in the choice of the next location to be visited. Overall, SLAW seems to benefit AODV in all aspects. However, this is due to the (static) way that SLAW builds (prebuilds) paths. In terms of CMM, it is interesting to note that the throughput results are similar to the ones obtained with RWP. This is again due to the fact that the variability with this model is higher, and periodic reconfiguration of the positions impacts the model, and consequently, the routing. This is even more noticeable for, e.g. SCNII and SCNIV, with high traffic load pattern, where CMM results in a decrease in throughput when compared with RWP. In terms of traffic load variation, there is also an expected impact when the network becomes congested. Again, the static nature of SLAW makes it less prone to packetes loss and, as a consequence, the difference between the application of low or high traffic load becomes less relevant when considering SLAW.

OLSR Impact

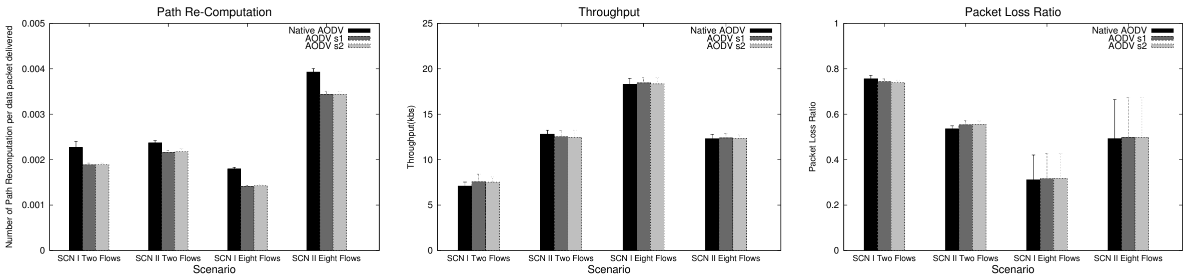
We have performed the same experiments with OLSR, and the results of normalized control overhead, throughput and packet loss are depicted in Figure 4.7. In what concerns normalized control overhead, RWP impacts the protocol with more severity, as observed in the lower achieved throughput and higher control overhead. SLAW, which achieved the lowest overhead in AODV, seems to increase such overhead in comparison to CMM, for both high load and low load traffic. Overall, OLSR exhibits more overhead also, a natural consequence of the way it propagates information. We believe that the difference in control overhead is due to the use of *Multipoint Relays (MPRs)* in OLSR. SLAW modeling provides specific way points, and as MPRs are defined once, such selection may not be suitable for subsequent way points.

Looking at the throughput results (cf. 4.7(b)), SLAW allows OLSR to exhibit the best results, while CMM and RWP result in similar loads. In comparison to AODV, the average throughput on the network is consistently lower than for AODV, which is a consequence of the nature of each protocol. Packet loss results ((cf. 4.7(c)) are similar to the ones achieved when considering AODV, and again, for the cases of a higher traffic load, they show that CMM has a similar behavior to RWP.

Summary

We have provided a study concerning the impact of three of the most popular mobility models in multi-hop routing. We have selected AODV and OLSR, as these are still the main multi-hop routing protocols in wireless ad-hoc networks. Our experimentation has considered the incorporation of several scenarios with different configurations of the three selected mobility models: different areas and high and low variable traffic patterns.

From the obtained results, we can corroborate that different mobility models significantly impact routing performance and can hinder the design of future solutions. Therefore, when creating routing solutions and when validating them via simulations, one may be considering wrong assumptions due to the applied mobility model. To serve as good validation tools, mobility models have to be as adequate as possible to represent realistic mobility scenarios. As noted in our experiments, CMM and SLAW resulted in varying performances in the two routing protocols. As a suggestion for a real validation using mobility models, we consider that more than one mobility model shall be employed and that RWP based models shall be avoided.



(a) Path Re-Computation. (b) Throughput. (c) Packet Loss.

Figure 4.8: Time-based Metrics ($s1$ and $s2$) Performance in AODV using RWP.

4.4.2 Performance Analysis of Time-based Routing Metrics (s1, s2)

This section presents the performance evaluation of routing metrics based on time-based family, discussed in the previous chapter, to determine the node suitability as a successor in the communication.The metrics were implemented in AODV, and experiments relied on the mobility scenarios and traffic load discussed in section 4. Next, we present the performance analysis of the two routing metrics s1 and s2.

Random Mobility Scenarios This section considers the mobility scenarios I and II, which depict nodes moving with random mobility patterns, and gives insight into the performance of metrics s1 and s2 (time-based), when applied to AODV.

Figure 4.8(a) depicts the performance results related to the average path re-computation. We compute this value based on the number of *route requests (RREQs)* generated and sent over the number of data packets received at the destination node. The aim is to understand if the metrics reduce the frequency of path re-computation due to link breaks on a data carrying route. The x-axis shows the two scenarios (*Scenario I (SCN I)* and *Scenario II (SCN II)*) with varying traffic load, and the y-axis shows the number of path re-computation, on average, per data packet received at the destination node.

Higher levels of node mobility variability among nodes increase the number of path re-computation, hence the disparity in the performance of the metrics in SCN I and SCN II. The increase of traffic flows means that more nodes actively participate in routing and the probability of link break on a route increases. This was the case for SCN II, but the converse is true for SCN I due to the exceptional high levels of mobility variability experienced by nodes on the routes of the two traffic flows of SCN I.

The proposed metrics outperform the benchmark routing metric due to their consideration of link break volumes of nodes, which penalize nodes with high volumes, hence avoiding them as successor nodes on routes. Metrics $s1$ and $s2$ perform very similarly in the two scenarios due to the ratio of link break duration; link break duration is the main defining factor when compared to the number of link breaks as nodes, on average in the two topologies, since there is a significant high number of link breaks.

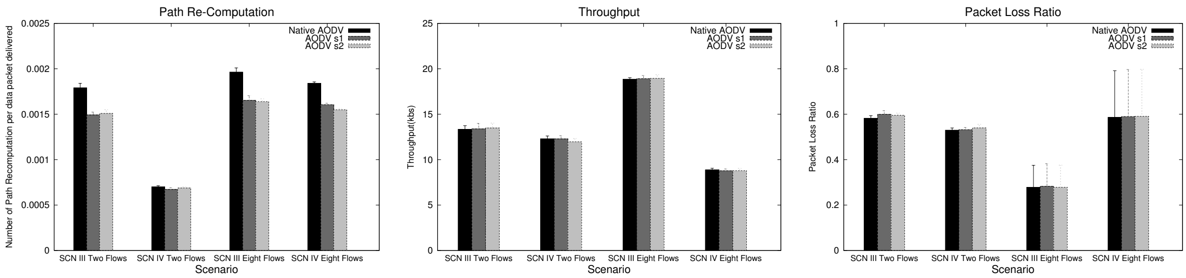
Figure 4.8(b) shows the performance of the metrics in terms of throughput. The aim is to analyse if the metrics reach the same level of throughput as the 'native' AODV. The achieved throughput of AODV with the proposed metrics in the two scenarios shows lower values for SCN II when compared to SCN I. This is due to the high levels of uncorrelated node mobility in SCN II when compared to SCN I, which is due to the increase in node speed of the random mobility of SCN II. The metrics in both scenarios perform similarly.

Figure 4.8(c) shows the performance of the metrics in terms of packet loss. The performance of the metrics are again very similar.

In RWP scenarios, the metrics $s1$ and $s2$ perform better than the native AODV. We continue validating the metrics using other mobility scenarios obtained from CMM, the first social mobility model.

Community-based Mobility Scenarios We discuss the performance of the metrics in scenarios III and IV, which depict nodes moving with *community-based mobility model (CMM)* mobility patterns. Figures 4.9(a) to (c) show the performance of the metrics in the two scenarios, *scenario III (SCN III)* and *Scenario IV (SCN IV)* respectively, with varying traffic load.

Figure 4.9(a) shows the performance of the metrics in terms of the path re-computation using the CMM mobility model. Lower levels of node mobility variability exist in CMM scenarios compared to RWP due to the presence of clusters in the former, with higher levels of link stability for nodes in CMM scenarios compared to RWP scenarios. CMM topologies are characterized by network partitions that lead to lower path re-computation with the increase in the node speed. The increase in the speed leads to nodes spending less time in transit from one cluster to another, hence, there is the unavailability of routes in some cases. As in RWP scenarios, the increase in traffic flows leads to more nodes actively involved in routing, increasing the chances of a break on



(a) Path Re-Computation. (b) Throughput. (c) Packet Loss.

Figure 4.9: Time-based Metrics ($s1$ and $s2$) Performance in AODV using CMM.

a route, and hence there is a higher frequency of path re-computation with the increase in traffic load.

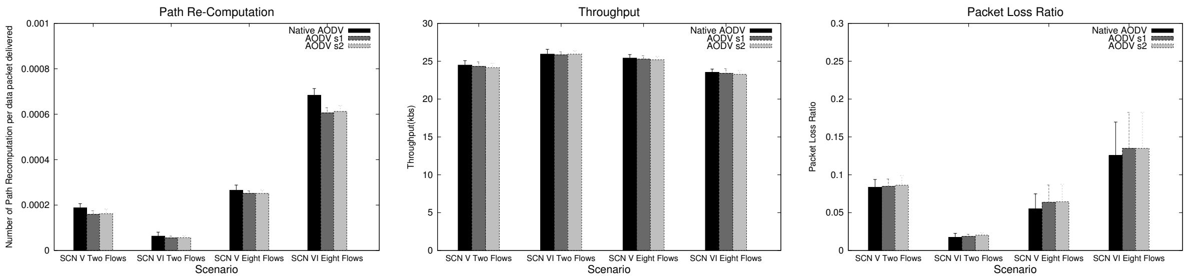
Considering the individual routing metric performance, metric $s1$ performs better in low traffic load because it considers nodes with link break duration ratio, where nodes that tend to stay long together provide better routes. Metric $s2$ has the best performance since it considers the number of link breaks in the node stability calculation.

Figure 4.9(b) shows the performance of the metrics in terms of achieved throughput using the CMM mobility model. The higher achieved throughput in CMM scenarios compared to RWP scenarios is due to the lower level of node mobility variability in the topologies. The presence of network partitions in the topology affects the achieved throughput due to the low number of routes present, resulting in lower achieved throughput in SCN IV compared to SCN III, which has less partitions. The increase in the traffic leads to more active nodes in the topology. In SCN III, better achieved throughput prevails at high traffic load due to the presence of clusters and to the presence of routes in case of inter-cluster routing. In SCN IV, the increase in traffic leads to lower achieved throughput due to the large presence of network partitions with minimal routes to use.

Considering the individual metric performance, all metrics behave similarly.

Figure 4.9(c) shows the performance of the metrics in terms of packet loss ratio using the CMM mobility model. Again, the metrics' performance is very similar.

Human Walk-based Mobility Scenarios (SLAW) We discuss the performance of the metrics in scenarios V and VI, which depict nodes moving with SLAW mobility model. Figures



(a) Path Re-Computation. (b) Throughput. (c) Packet Loss.

Figure 4.10: Time-based Metrics ($s1$ and $s2$) Performance in AODV using SLAW.

4.10(a) to (c) show the performance of the metrics in the two scenarios.

Figures 4.10(a) illustrates the path re-computation in SLAW scenarios. SLAW scenarios depict human walk and provide the lowest levels of node mobility variability in the mobility scenarios under study. As such, the lowest levels of path re-computation are obtained. Again, the increase in traffic load leads to the increase in path re-computation for the reasons explained above. SCN V depicts a scenario where nodes have less tendency to move to nearer destinations compared to SCN VI, meaning that there are higher levels of node mobility variability in the former compared to the later. This results in a larger number of path re-computation in SCN V compared to SCN VI under low traffic load. The increase in traffic load means that more nodes are actively involved in routing, and as above, more path computation occurs under high traffic load, due to the increase in the probability of link break. SCN VI seems to be more affected by the increase in traffic load because fewer nodes are involved in inter-cluster routing compared to SCN V, leading to fewer alternative paths to use for inter-cluster routing.

Considering the individual routing metrics performance, both proposed metrics behave better than the benchmark metric with metric $s1$ being the best. SLAW scenarios are characterized by node clustering and slow moving nodes, and the metric that considers link break duration ratio only achieves slightly better performance.

Figure 4.10(b) shows the performance of the metrics in terms of achieved throughput under SCNV and SCNVI. The performance is similar with high values of achieved throughput due to the high levels of node stability in the two topologies compared to RWP and CMM scenarios.

Figure 4.10(c) shows the performance of the metrics in terms of packet loss. The metrics behave similarly with minor variations of less than 2% in the obtained packet loss ratios.

Discussion

The study of these routing metrics based on time-based family shows that both $s1$ and $s2$ metrics improve the routing protocol robustness through the reduction in path re-computation, meaning that more stable nodes are involved in routing compared to native AODV.

In terms of which metric seems to be better, we have selected $s2$ as it seems to perform better in scenarios where there is a high presence of node mobility variability due to its exploitation of the number of link breaks that a node incurs on its links. On the other hand, metric $s1$ seems to perform better in scenarios with lower levels of node mobility variability such as in SLAW mobility scenarios.

Given that the human mobility patterns affect routing performance as shown in section 4.4.1, using the two routing metrics reduces the impact that node mobility has on routing performance. This is attested by the reduction in the path re-computation by the routing protocol, meaning that the protocol becomes robust to node mobility using metrics of link history based family.

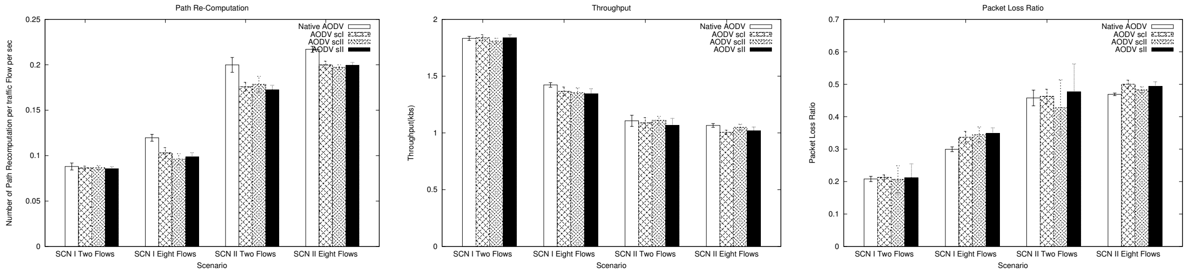
In the next sub-section we shall give insight into the spatial correlation metrics, starting with $sc1$ and $sc2$. To better understand their behavior in comparison to the metrics derived from the time-based family, we shall rely on $s2$ solely given the fact that both $s1$ and $s2$ showed similar performance in AODV, with $s2$ providing slightly better results in comparison to $s1$.

4.4.3 Performance Analysis of Spatial Correlation Routing Metrics (sc1 and sc2)

This section evaluates the spatial correlation metrics $sc1$ and $sc2$, which in the figures is also denoted as sII . We include in this set of experimens $s2$ in order to better show the differences of behavior that may arise from applying a spatial-correlation metric, or a time-based metric. The metrics have been implemented in AODV and OLSR, and mobility scenarios I to IV have been used with mobility characteristics as depicted in tables 4.3, 4.4 and 4.5. The traffic model used is based on table 4.6.

AODV Scenarios

This section depicts the results and performance analysis of the metrics using the routing protocol AODV.



(a) Path Re-Computation. (b) Throughput. (c) Packet Loss.

Figure 4.11: Spatial Correlation based Metrics ($sc1$ and $sc2$) and $s2$ Performance in AODV using RWP.

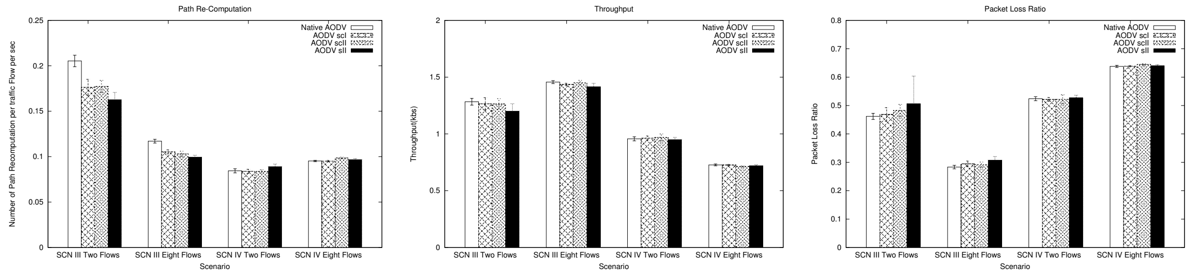
RWP Scenarios Figures 4.11(a) to (c) depict the performance of the metrics in scenarios I and II (SCNI and SCNII, respectively), which depict nodes moving with random mobility patterns.

Figure 4.11(a) provides results related to the average path re-computation of the routing metrics.

The increase in path re-computation from scenario I to scenario II relates with higher node mobility, and ultimately more link breaks in the topology. The first observation we make is that any of the proposed metrics excels the regular AODV performance in terms of path re-computation reduction, while at the same time attaining good performance (throughput, packet loss), very similar to the behavior of the native AODV. When network load increases (from 2 to 8 flows), and for the specific case of scenario I (random movement), metric $sc2$ improvesthis behavior. We believe this relates with the topology derived from the application of RWP in this specific scenario. With an increase in traffic variability, $sc2$ provides more robustness as it takes into account groups of nodes with similar movement. The observed improvement is, however, incremental. One hypothesis we left to be verified in future work is that a metric derived from $s2$, capable of keeping state, could improve its behavior in scenarios with more traffic variability.

CMM Scenarios In order to understand whether or not the metrics are experiencing side issues due to the type of movement modelled we repeat the scenarios provided in the prior section, but replace RWP with another mobility model, CMM. The main difference from the application of CMM to RWP is that RWP is based in brownian motion for individual nodes, while CMM is based on social interaction, and considers node movement from a group perspective.

Figure 4.12(a) shows the performance of the metrics in terms of path re-computation when



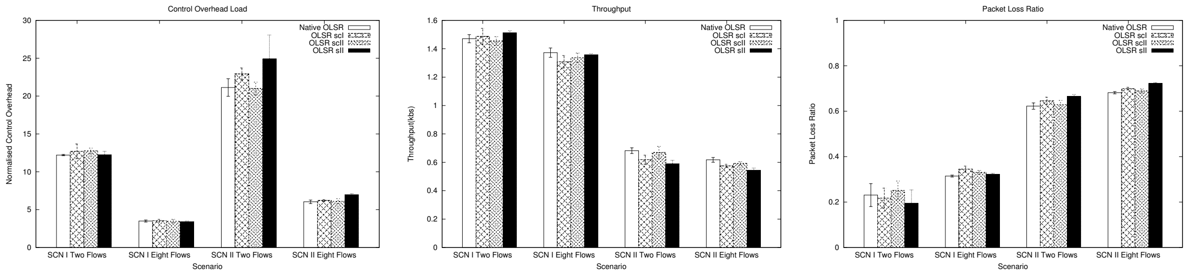
(a) Path Re-Computation. (b) Throughput. (c) Packet Loss.

Figure 4.12: Spatial Correlation based Metrics ($sc1$ and $sc2$) and $s2$ Performance in AODV using CMM.

considering CMM. A first relevant observation to make is that the two models have quite different performance results. CMM scenarios result in significantly lower path re-computation compared to RWP scenarios, due to the presence of clusters lowering node mobility variability in the topologies. The increase of speed (SCN IV) leads to higher prevalence of network partitions resulting in significantly lower path computation compared to nodes at low speed (SCN III). As there is an increase in network partitions, the results attained in Scenario IV are quite similar for both models. From a metric perspective, $s2$ is again the metric that seems the most stable when considering the results globally. In scenario IV, and for light traffic scenarios, however, it is $sc2$ the metric that performs better. This seems to imply that this metric is the one that is less sensitive to a change in mobility patterns.

We analyse also results for the achieved throughput and packet loss, in order to understand if the computation required by our metrics would negatively impact the network performance. As shown in Figures 4.12(b) and (c), the results achieved by integrating our metrics are similar to the results attained with native (hop count based) AODV. $s2$ shows, in a few cases of low traffic load (2 flows), more variability than the other metrics, a consequence of a higher volume of network partitions, we believe. As the metric is based on link break duration, network partitions significantly impact the performance of this metric.

We proceed in the next sections with an analysis of the metrics' performance in OLSR.



(a) Control Overhead. (b) Throughput. (c) Packet Loss Ratio.

Figure 4.13: Spatial Correlation based Metrics (*sc*1 and *sc*2) and *s*2 Performance in OLSR using RWP..

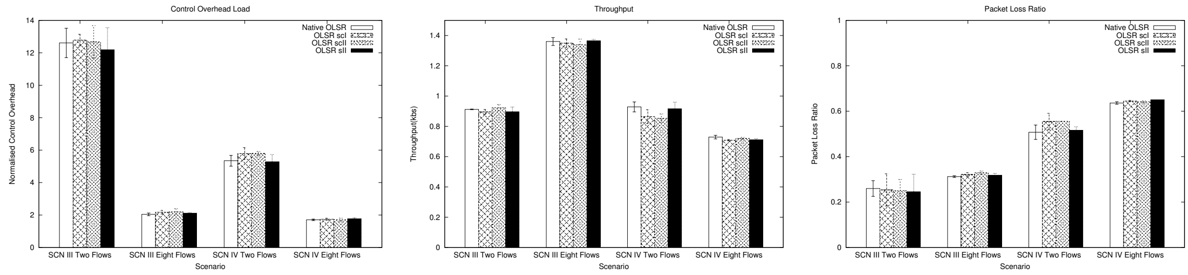
Impact on OLSR

This section analyses the metrics performance using the routing protocol OLSR. While for the case of AODV we have considered path re-computation as the main performance parameter, for OLSR we will consider the control overhead. In this set of experiments, we have also added a thid mobility model, SLAW, as this model exhibits a more static behavior (Levy Walk based waypoints).

RWP Scenarios Figures 4.13(a) to (c) show the performance of the metrics in the two scenarios.

Figure 4.13((a) illustrates the normalized control overhead incurred during the simulation period. This is the ratio between the *Topological Control (TC)* packets of OLSR and the data packets sent. The aim is to understand if the metrics use optimal nodes for *Multipoint Relays (MPR)* to be used as relays in the face of node mobility. The x-axis shows the mobility scenarios and the y-axis shows the normalized control overhead during the simulation time.

Overall, *sc*2 seems to be the metric with the best performance even though the difference towards the other metrics is low. As in AODV, the increase in node mobility leads to more routing control overhead. The lower normalized control overhead with increased traffic load is due to more data packets being received compared to the case of low traffic load. Figure 4.13((b) illustrates the performance of the metrics in terms of achieved throughput. The increase in node mobility variability greatly affects the achieved throughput as shown in the results obtained in SCN I and SCN II. The increase in traffic load leads to lower overhead, due to the increase in active



(a) Control Overhead. (b) Throughput. (c) Packet Loss Ratio.

Figure 4.14: Spatial Correlation based Metrics ($sc1$ and $sc2$) and $s2$ performance in OLSR using CMM.

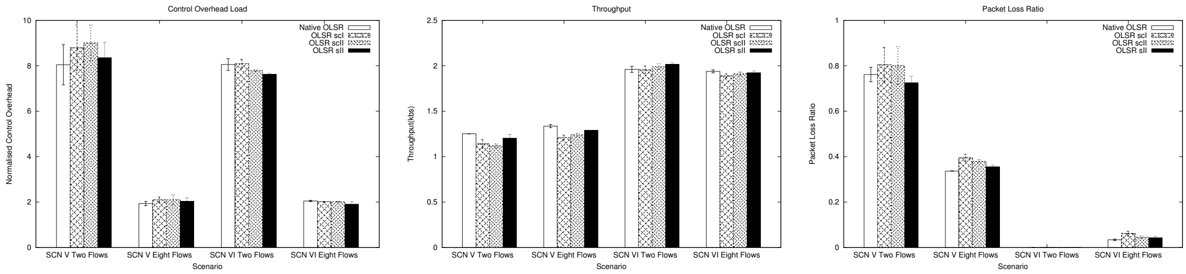
nodes being subjected to node mobility variability. On average, the metrics perform similarly. This is attested by the packet loss ratios, which show similar results with minor variations as shown in figure 4.13((c).

CMM Scenarios

We discuss the performance of the metrics in scenarios III and IV, which depict nodes moving with CMM mobility patterns. Figures 4.14(a) to (c) show the performance of the metrics in the two scenarios which, in the legend, are shown as SCN III and SCN IV, respectively, with varying traffic loads.

Figures 4.14(a) to (c) show the performance of the metrics in the two scenarios, denoted as SCN III and SCN IV, respectively, with varying traffic load. Figure 4.14(a) shows the performance of the metrics in terms of normalized control overhead in scenarios III and IV. Due to the presence of clusters, unlike in RWP scenarios, CMM scenarios have, on average, lower control overhead. Like in AODV, under CMM, the presence of network partitions influence the metrics performance to have lower control overhead in SCN IV compared to SCN III. The increase in traffic load leads to more data packets being received, lowering the average control overhead as more data packets are routed in high traffic load compared to low traffic load.

From a metric perspective, $sc2$ and $s2$ perform better overall. The increase in the node speed (SCN IV) leads to high prevalence of network partitions, and as such, metrics behave similarly. Figure 4.14(b) shows the performance of the metrics in terms of achieved throughput using the CMM mobility model. The higher probability of routing within clusters with the increase in



(a) Control Overhead. (b) Throughput. (c) Packet Loss Ratio.

Figure 4.15: Spatial Correlation based Metrics ($sc1$ and $sc2$) and $s2$ Performance in OLSR using SLAW.

traffic load leads to higher achieved throughput in SCN III under high traffic load compared to low traffic load. On the other hand, high prevalence of network partitions affect more SCN IV with high traffic load, on average, leading to lower achieved throughput compared to low traffic load. On the individual metric performance, routing metrics behave similarly, and this also results in lower packet loss ratios for the two metrics as shown in figure 4.14(c).

SLAW Scenarios We discuss the performance of the metrics in scenarios V and VI, which depict nodes moving with SLAW (Figures 4.15(a) to (c)).

Figure 4.15(a) illustrates the performance of the metrics in terms of the normalized control overhead generated for scenarios V and VI. Comparing with other scenarios, metrics under SLAW achieve the lowest control overhead due to the lower node mobility variability prevalent in the two mobility scenarios, as also noted under AODV. The slightly higher node mobility variability of SCN V compared to SCN VI leads to slightly higher control overhead in SCN V compared to SCN VI. Due to the higher possibilities of routing within clusters with the increase in traffic flows, the obtained results under high traffic load are very similar in both mobility scenarios, being again $sc2$ and $s2$ the metrics that provide the best performance across all scenarios. Considering the individual routing metrics performance $s2$ is the one best performing again for the same reasons mentioned above. Figure 4.15(b) and (c) illustrate the performance of the metrics in terms achieved throughput and packet loss. Lower node mobility variability in SCN VI leads to higher achieved throughput compared to SCN V. Due to the low levels of node mobility variability, the increase in traffic load has a small impact on the achieved throughput. This is the case in our scenarios because there is no congestion in the topologies.

Discussion

In this section we have provided results concerning spatial correlation metrics $sc1$ and $sc2$, which were were validated both in the context of AODV and OLSR, for scenarios that integrate different mobility models. In this set of experiments, $s2$ has been used as a representative example of a time-based mobility-aware routing metric.

A first conclusion to draw is that, overall, any of the metrics proposed provides improvements both for AODV (reduction in path re-computation in the order of 15%) and for OLSR (reduction in signaling overhead in the order of 8%).

A second conclusion to draw is that there are two metrics that stood out, $sc2$ and $s2$. From these two, $sc2$ seems to provide slightly better results with AODV than with OLSR. While $s2$ is the metric that provided better performance from a global perspective and for both protocols. We believe that one of the reasons for this difference relates to the selection of MPRs. $sc2$ is more affected by such (static) selection, as it integrates the notion of stability also in terms of group.

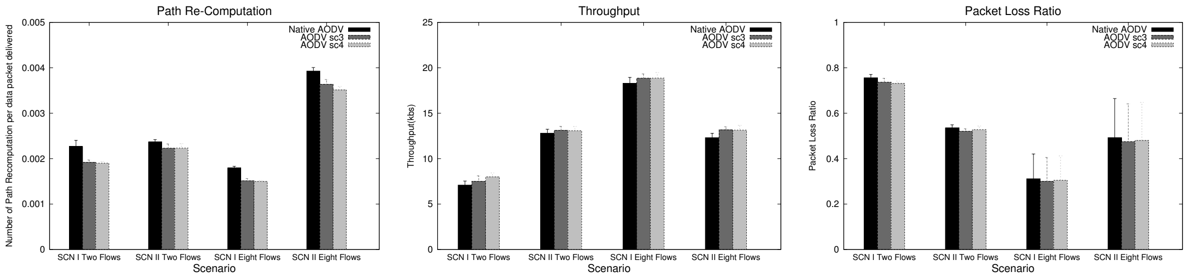
4.4.4 Performance of Metrics Based on Node Spatial Correlation, and Perspective of Source and Successor Node ($sc3$ and $sc4$)

$sc1$ and $sc2$, analysed in the prior sections, integrated a single node perspective. In this section we analyse the performance of $sc3$ and $sc4$ which are spatial correlation metrics, which incorporate the movement perspective captured by a source and successor nodes, for AODV.

Random Scenarios

We discuss the performance of the metrics in scenarios I and II, which depict nodes moving with random mobility patterns. Figures 4.16(a) to (c) show the performance of the metrics in the two scenarios.

Figure 4.16(a) shows the performance results with respect to the average path re-computation. We notice that higher levels of mobility variability among nodes bring more path re-computation, hence there is a divergence between SCN I and SCN II. The increase of traffic flows means that more nodes actively participate in routing, and the probability of link breaks on a route increases. This is the case for SCN II, but the converse is true for SCN I due to the exceptional high levels of mobility variability experienced by the 2 flows in SCN I. Considering the individual metrics



(a) Path Re-Computation. (b) Throughput. (c) Packet Loss.

Figure 4.16: Spatial Correlation based Metrics ($sc3$ and $sc4$) Performance in AODV using RWP.

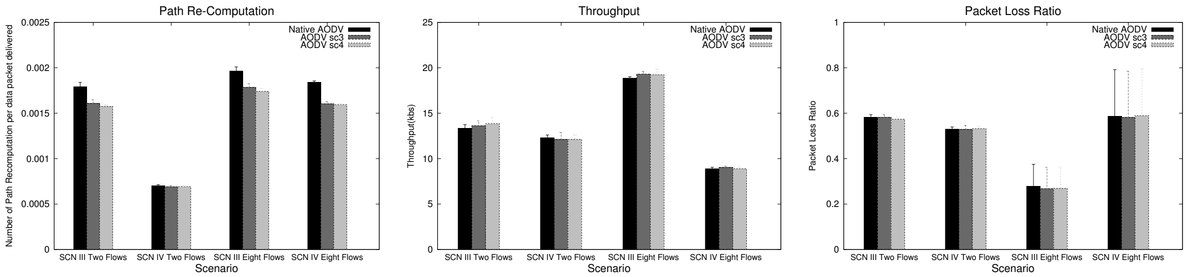
performance, both metrics ($sc3$ and $sc4$) perform better than the benchmark metric, due to their consideration of node mobility variability when choosing the successor nodes. Metric $sc4$ performs even better due to its average link duration, which is seemingly showing more sensitivity to node mobility.

Figure 4.16(b) shows the performance of the metrics in terms of achieved throughput using the RWP mobility model. The high levels of mobility variability experienced in SCN I with low traffic load also lead to a lowest achieved throughput and highest packet loss ratio as shown in figure 4.16(c). Considering the individual metric performance, the metrics behaved similarly with a slight improvement by our metrics, due to the reduced path computation lowering the control overhead. This is the case also in terms of packet loss as shown in figure 4.16(c).

CMM Scenarios

We test another mobility model, *CMM,* in order to understand the impact of a mobility model in the performance metrics. Figures 4.17(a) to (c) show the performance of the metrics in the two scenarios, *scenario III (SCN III)* and *Scenario IV (SCN IV),* respectively with varying traffic loads.

Figure 4.17(a) shows the performance of the metrics in terms of path re-computation using CMM. Lower levels of node mobility variability exist in CMM scenarios compared to RWP, due to the presence of clusters in the former, bringing higher link stability for nodes in CMM scenarios compared to RWP scenarios. CMM topologies are characterized by network partitions that lead to lower path re-computation with the increase in node speed. The increase in speed leads to



(a) Path Re-Computation. (b) Throughput. (c) Packet Loss.

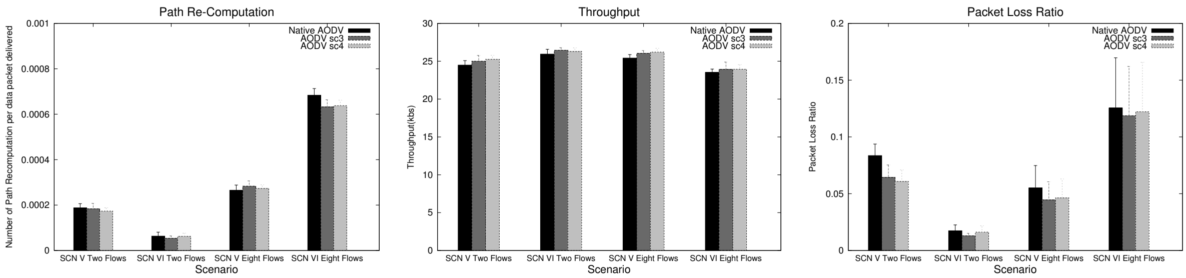
Figure 4.17: Spatial Correlation based Metrics (*sc*3 and *sc*4) Performance in AODV using CMM..

nodes spending less time in transit from one cluster to another, hence there is the unavailability of routes in some cases. As in RWP scenarios, the increase in traffic flows leads to more nodes actively involved in routing, increasing the chances of a break on a route and a higher path re-computation.

Considering the individual metrics performance, the proposed metrics, perform better than the benchmark metric in all scenarios. Metric *sc*4 seems to be the one outperforming the other metrics due to its consideration of node average link duration thereby supporting routing more within clusters.

Figure 4.17(b) shows the performance of the metrics in terms of achieved throughput using the CMM mobility model. Higher achieved throughput prevails in CMM scenarios compared to RWP scenarios, due to the lower levels of node mobility variability in the topologies. The presence of network partitions in the topology affects the achieved throughput due to the low number of routes present, resulting in lower achieved throughput in SCN IV compared to SCN III. The increase in the traffic leads to more active nodes in the topology. In SCN III, better achieved throughput prevails at high traffic load due to the presence of clusters and also the presence of routes in the case of inter-cluster routing. In SCN IV, the increase in traffic leads to lower achieved throughput due to the high presence of network partitions with minimal routes to use.

Figure 4.17(c) shows the performance of the metrics in terms of packet loss ratio using the CMM mobility model, with similar performance.



(a) Path Re-Computation. (b) Throughput. (c) Packet Loss.

Figure 4.18: Spatial Correlation based Metrics ($sc3$ and $sc4$) Performance in AODV using SLAW.

SLAW Scenarios

We discuss the performance of the metrics in scenarios V and VI, which depict nodes moving with SLAW mobility patterns, shown in Figures 4.18(a) to (c).

Figure 4.18(a) illustrates the amount of path re-computation in SLAW scenarios. SLAW scenarios depict human walk and provide the lowest levels of node mobility variability in the mobility scenarios under study. As such, the lowest levels of path re-computation are obtained. Again, the increase in traffic load leads to an increase in the path re-computation for the reasons explained above. SCN V depicts a scenario where nodes have less tendency to move to popular destinations compared to SCN VI, meaning that there are higher levels of node mobility variability in the former compared to the later. This results in higher path computation in SCN V compared to SCN VI under low traffic load. The increase in traffic load means that more nodes are actively involved in routing, and as above, more path computation occurrs under high traffic load due to the increase in the probability of link break with the increase of routing paths. SCN VI seems to be more affected by the increase in the traffic load because fewer nodes are involved in inter-cluster routing compared to SCN V, leading to fewer alternative paths to use in inter-cluster routing. Considering the individual routing metric performance, no single routing metric is outstandingly the best, due to the high stability levels of nodes in these two topologies. However, metrics $sc1$ and $sc2$ seem to perform better than native AODV overall. This is because they consider levels of node mobility variability when choosing the successor node.

Figure 4.18(b) illustrates the performance of the metrics in terms of achieved throughput. In both scenarios, the achieved throughput is relatively high due to the high number of stable links;

however, there is some variability in our metrics, although non-significant.

Figure 4.18(c) shows the performance of the metrics in terms of packet loss. Overall, metrics perform very similarly.

Discussion

In this set of experiments we have considered a second set of spatial correlation metrics, *sc*3 and *sc*4, and have applied them in the context of AODV.

The proposed routing metrics (*sc*3 and *sc*4) performed better than the benchmark routing metric with maximum gain of 18%. From an individual perspective, across all scenarios, *sc*4 showed slightly better results than *sc*3, even though this improvement is not significant.

Comparing the results obtained from this set of experiments against the results obtained for AODV by relying on *sc*1 and *sc*2, under the same conditions, a first observation is that *sc*3 and *sc*4 provided similar results and in what concerns packet loss, more variability for scenarios with a heavier traffic load, when comparing the attained results to the results obtained with native AODV.

From this extensive set of experiments we can conclude that mobility-aware metrics derived from the ones proposed can improve routing robustness in scenarios with movement variability.

4.5 Summary

This chapter discussed the impact of human mobility patterns in the evaluation of the proposed mobility metrics. The obtained results showed that human mobility patterns affect routing, and individual mobility characteristics played different roles. For example, mobility induced by social attraction may result in a higher variability. Other mobility parameters, such as speed, may exhacerbate the impact, as nodes main remain in each other's communication range for short periods of time, while moving. In contrast, the tendency to re-visit preferred locations creates scenarios with less variability.

The proposed metrics were evaluated via simulations carried out with the discrete event simulator ns2.34, and the results obtained showed the reduction in path re-computation when the proposed metrics were used. This means that the routing protocol used became more robust in dynamic environments, e.g., UCNs. The two routing metric families increase the routing robustness to node mobility. However, the improvements were more pronounced in AODV when compared to OLSR, aspect which we believe to be related with the MPR selection process, an aspect that needs to be tackled in future work.

In what concerns whether or not there are "best" metrics, the ones that exhibited better performance were $sc2$, $s2$, and $sc4$. In terms of spatial correlation, $sc4$ shows better performance in comparison to $sc2$, even though such improvement is small. This implies that it is relevant to incorporate into future utility functions both the perspective of the source node and its successor, given the fact that the state required by $sc4$ is insignificant in comparison to the state required to compute and to update $sc2$.

In what concerns the time-based family vs. the spatial correlation family, $s2$ exhibited a similar performance to $sc2$ (and consequently, to $sc4$). Our belief is that the spatial correlation metric is more stable; however, in scenarios where individual mobility may be more proeminent (such as in delay tolerant networking) then $s2$ may be a more suitable metric.

Chapter 5

Conclusions and Related Challenges

This thesis analysed and proposed metrics to improve current multi-hop routing. A key requirement of the thesis was to understand up to which point could routing become more sensitive to movement of nodes and hence, naturally and dynamically avoid unnecessary path re-computation. In our work, we have therefore explored an alternative perspective, namely, to propose and to validate routing metrics that are mobility-aware, requiring minor changes to the protocol design (in the context of shortest-path routing solutions).

A first finding concerns the impact of different mobility features in current multi-hop routing approaches based upon shortest-path computation, in contrast to other algorithmic features, such as temporarily-ordered routing. Therefore, a first contribution of this work relates to a better understanding of the mobility-aware parameters that can be easily integrated into routing. Moving beyond speed, acceleration offset as well as visits to preferred networks, our work delved into metrics that take into consideration aspects such as link duration and neighborhood characterization.

A second finding relates to the development of metrics that make multi-hop routing approaches more tolerant to mobility aspects that reflect regular movement patterns (e.g., ping-pong effect). We have shown, in chapter 3, how the different analysed and new parameters could be combined into different metrics without affecting significantly the natural processing of routing protocols. We have also explained how these parameters assist in bringing in more stability to the selection of node successors, and hence, to the global path computation process.

A third finding relates to the challenge of understanding whether or not shortest-path routing could be truly suitable for networking environments where nodes attain a high degree of freedom in movement. The validation of the different metrics shows that shortest-path routing can be improved by integrating parameters capable of tracking specific mobility aspects.

Out of the validated metrics, $s2$ is the one that, across experiments involving different mobility models, providedbetter results. This metric tends to avoid selecting as successor nodes that have large volumes of link breaks. By avoiding nodes with high volumes of link breaks, the resulting paths consist of familiar nodes that tend to spend stable periods of time in each other's communication range.

For AODV, the metrics that provided best results are $sc4$ and $s2$. $sc4$ seems to be beneficial (in contrast to $s2$) in scenarios where mobile nodes tend to cluster, and $sc4$ chooses nodes that have relatively low mobility variability with their respective neighboring nodes.

For OLSR, we have only run experiments involving $sc1$, $sc2$, and $s2$. Out of these, $sc2$ and $s2$ again showed better performance. $s2$ provided slightly better performance for scenarios with low traffic. This behavior seems to be justified due to the fact that scenarios that run a smaller number of hops can avoid link breaks on a path, as the probability of a break increases with the increase in the number of hops on a path.

We have shown also that path re-computation can be reduced by integrating these metrics without a significant impact in the protocolar operation and design.

5.1 Conclusions

Based on our work, the following conclusions can be drawn:

- Different mobility patterns impact significantly multi-hop routing, as shown in section 4.1 by the varying performances of the two routing protocols AODV and OLSR, when subject to three different mobility models, RWP, CMM, and SLAW. Random mobility leads to higher control overhead and frequency of path re-computation. Acceleration leads to a high number of link breaks in topologies of random mobility or moving towards social attractions. On the other hand, the tendency for humans to cluster and to move to the nearest destinations leads to more stable routing compared to when nodes moved to next destinations with lower tendency to move to the nearest one.

- We have ran simulations across six different mobility scenarios and we have shown, via simulations, that routing can become more robust in dynamic environments, if mobility-aware metrics are used. Our metrics reduced the impact of node mobility compared to native AODV and, to some extent, OLSR. As benchmark we have considered native AODV and OLSR behavior (path computation based on hop count), and it has been shown that the native versions of these protocols are not enough to deal with dynamic routing environments, where mobility creates topological variability.

- The increase in traffic load led to an increase in the frequency of path re-computation in AODV, as it is a reactive routing protocol. Our metrics also varied with the increase in the traffic; however, they always performed better than the benchmark metric.

- When applying time-based metrics ($s1$ and $s2$) and spatial correlation metrics ($sc1$ to $sc4$) to AODV, all metrics showed improvements, having $s2$ (time-based) and $sc4$ (spatial correlation based) provided the best performance.

- When applying time-based metrics ($s2$) and spatial correlation metrics ($sc1$ and $sc2$) to OLSR, there was a slight increase in control overhead. We believe this relates to the MPR static selection, which needs to be adjusted in future work, to integrate also mobility awareness. The metrics that performed the best with OLSR were $sc2$ (spatial correlation) and $s2$(time-based).

- In the simulations, RWP, CMM and SLAW mobility scenarios were used. The routing metrics, including benchmark, performed differently in the different scenarios, with RWP having more control overhead and higher frequency of path re-computation; in the SLAW mobility scenarios, the metrics were least affected. This is attributed to the high level of mobility variability brought due to the random mobility pattern, while in the case of SLAW scenarios, the tendency to spend time in preferred locations and choosing the nearest destinations led to least node mobility variability. In all these cases, using our routing metrics, the following hapenned: in AODV it led to reduced frequency of path re-computation, while in OLSR the improvement was not as significant as in AODV. The change in node speed led to more control overhead in the routing protocols; however, our metrics reduced this impact of mobility by incurring less path re-computation.

Main Findings

In this section we provide the main findings of our work, against the proposed initial goals (described earlier in chapter 1).

- *What is the impact of different mobility features in current single-source shortest-path approaches?*

  – Node mobility impacts routing, and different aspects (such as link length, mobility pattern, specific routing phase) of node mobility play a role to determine when node mobility becomes significant. Hence, routing protocols should be made mobility-aware in their design. Novel metrics, such as the ones proposed, can be integrated easily in past and future protocols, and may potentially be combined with other metrics such as QoS metrics.

  – The mobility parameters available in related literature and used to capture node mobility did so partially.

  – Out of our proposed metrics, we advocate the integration of a source and successor perspective, in contrast to the perspective of a single node.

- *How can routing mechanisms become more tolerant to mobility aspects that reflect regular movement patterns (e.g., ping-pong effect)?*

  – Specific families of metrics can assist in creating more robust enviroments. We have shown that the spatial correlation metrics are more relevant in scenarios where nodes tend to cluster. While the time-based approaches seem to be more relevant in scenarios where nodes exhibit regular movement (such as the ping-pong effect).

  – For the case of OLSR, it is also necessary to address MPR selection by incorporating mobility-awareness features, an aspect which we did not look into.

- *Is shortest-path routing truly suitable for networking environments where nodes attain a high degree of freedom in movement?*

  – Shortest path routing is not, in its native form, suitable for networking environments with variable topologies, due to node movement. We have shown in chapter 4 the impact that different mobility models have in the most proeminent multi-hop routing protocols in operation as of today. Hence, it is relevant to consider that new routing approaches must integrate into their design mobility-aware features.

- *Can other-than-shortest-path approaches (alternative routing approaches) improve the network robustness?*
  - We have shown that by integrating mobility-aware routing metrics into available protocols, their robustness improves in terms of path recomputation and subsequent overhead.
  - Out of the proposed metrics, $s2$ (time-based) and $sc4$ (spatial correlation) metrics were the ones providing better performance in AODV. While for OLSR, the experiments run were limited to $sc1$, $sc2$, and $s2$. Again for OLSR, $sc2$ and $s2$ showed the best performance.

5.2 Related Challenges

In this section we provide a summary of issues that do not directly relate with the thesis focus, albeit these issues are in our opinion essential to the integration of the proposed metrics, in an adequate way.

5.2.1 Scalability Aspects

Scalability of multi-hop routing protocols has been studied, and a number of factors affect routing protocol scalability. These are mainly the number of nodes and mobility [87]. We discuss our routing metrics and their expected performance in terms of increased nodes in a topology, change of node degree, increase in network partitions and node mobility, which are factors affecting routing protocol scalability.

Number of Nodes in the Network Topology

We analyse the effect of increased the number of nodes in a topology on our metrics, according to the routing metric families.

Spatial Correlation-based Routing Metric Family This category of routing metrics is not affected by the increase in the number of nodes in a topology because the information a node maintains for metric computation remains the same, and what changes is the content which reflects node mobility variability, such as the link duration or node degree. Each node relies on its own observed information to acquire metric parameter values.

Time-based Metric Family Nodes in routing scenarios that employ this category of routing metrics keep record of link activities. As such, in the case of the increase in the number of nodes in a topology, the effect of keeping more states for valid neighbors is mainly dependent on the node degree. When there is a high level of node variability in the topology, this category has to keep state of broken links for some time before an entry expires and can be deleted. This may lead to a node keeping state for a large number of entries in cases of high node variability combined with high number of nodes in a topology.

Frequency Network Partitions

We discuss the performance of our metrics with regard to high frequency of network partitions. A high frequency of network partitions affects routing performance, and all routing metrics behaved similarly as there are limited or no possible routing paths to be created for data transfer. Since the creation of network partition is a result of node mobility, routing metrics that are not mobility-aware are expected to be affected more. However, this does not mean that mobility-aware routing metrics are immune.

Spatial correlation-based Routing Metric Family This family of routing metrics is expected to be affected by high frequency of network partitions like any other metric. However, since partitions are a result of node mobility, and given that these metrics consider stability of a neighbor set to determine node mobility variability, we expect reduction in the negative impact of network partitions when routing occurs within clusters where stable neighbor sets exist.

Time-based Routing Metric Family This category of routing metrics considers link break volumes to choose the successor node. A high frequency of network partitions is incurred through link breaks from node mobility which routing metrics are not agnostic to. Although these metrics are affected by partitions, the severity of the impact is expected to be lower, as they take into consideration link break volumes when building routing paths.

Node Mobility

Node mobility, as shown in our study, has an impact on routing performance. Because our metrics are mobility aware, as shown in section 4.4, the impact of node mobility is decreased.

5.2.2 Security Aspects

Security threats in a wireless network can be a reality in different layers of the protocol stack [2][85]. A number of security attacks target one protocol layer while others are multi-layer [85]. For example, Denial of Service is a multi-layer attack while Jamming, interceptions and eavesdropping target the physical layer. For network and link layers, there is flooding and a disruption of MAC, respectively, to mention a few.

As far as security aspects are concerned, our work does not alter security of routing protocols in any way.

5.2.3 Quality of Service (QoS) and Energy Aspects

To support multimedia and other applications, it is desirable that an ad-hoc network has the capability to provide the required levels of Quality of Service (QoS) [3]. End-user devices, which act as networking nodes, have limited resources in terms of energy. Inefficient consumption of this limited resource results in nodes dying out due to energy exhaustion, hence shortening the network lifetime. Improving energy consumption efficiency improves node lifetime and ultimately, network lifetime.

Quality of Service in Relation to Node Mobility

Some of the challenges of provision required QoS levels in a network are network topological changes and link characteristic changes [83]. Node mobility causes changes in wireless links in terms of capacity as well as topological changes as links break. Frequent changes in network topologies make QoS sustenance difficult, as paths for routing data are short lived and also routing performance is affected due to frequent path computation in route discoveries. Perkins *et al.* argue that mobility-induced path failure increases packet loss rates, end-to-end delay, and communication overhead, and that it is a key obstacle to improving QoS in ad-hoc networks [64].

We have devised routing metrics that can reduce the frequency of path re-computation in dynamic environments through the use of stable nodes, in terms of mobility, as successor nodes. By using stable routes to transmit data, the effect of network topological changes that affect QoS is also reduced. Our metrics will choose stable nodes in terms of mobility as successor nodes, and this will result in having nodes with less relative mobility variability on routes, hence improving QoS.

Energy Consumption in Relation to Node Mobility

Mohsin *et al.* discussed packet transmission and receipt as some of the procedures where energy is consumed [57]. Energy Efficient Location Aided Routing protocol, to reduce energy consumption, reduces the area for new route discoveries, reducing control overhead in a network topology [56]. Since node mobility in multi-hop routing causes routing paths to break, and this results in the increase in the control overhead, we can infer that node mobility causes increased energy consumption. Like in QoS, where reduction in frequency of path re-computation can result in improved QoS, we believe that if control overhead increase is reduced by mobility aware routing metric, energy consumption by network nodes can be reduced.

5.2.4 Routing Metric Performance in Cluster-based and Geographic Routing Protocols

A number of categories of multi-hop routing protocols exist, as discussed in section 2.3. The proposed metrics have been implemented in on demand and proactive routing protocols. We discuss the expected performance of our metrics in two other main categories of multi-hop routing protocols. These are Cluster-based and geographic routing protocols.

Routing Metric Performance in Cluster-based Multi-Hop Routing Protocols

Cluster-based multi-hop routing protocols group nodes into clusters, where one node becomes a cluster head and other nodes of a cluster assume cluster membership role [88]. Path discovery is performed on a cluster to cluster basis, as the cluster head knows its membership to determine if the destination node is in its cluster, thereby reducing flooding during the path discovery phase.

Node mobility is critical to cluster sustenance. The length of cluster validity depends on the presence of correlated node mobility or the absence of node mobility. Unstable clusters lead to the degradation of the benefit of clustering attained by reduced control messages during path discovery. We discuss how our metrics can enhance clustering schemes by increasing mobility awareness through cluster creation using our metrics.

For time-based metrics, clusters are formed based on low link break volumes in a node with high number of neighbors with low link break volume as cluster head. In consideration of metrics based on space, cluster stability is attained with nodes with high spatial correlation. A node with higher stability in terms of spatial correlation becomes the cluster head and neighbors are the cluster members.

Our metrics enhance strong cluster formation by taking into consideration node mobility characteristics.

Routing Metric Performance in Geographic Multi-hop Routing Protocols

In topologies using geographic multi-hop routing protocols, nodes use location information for packet delivery [49]. Nodes locally exchange neighborhood information. Location information determines routing decision of the next hop on a routing path [75][49]. The down side of this approach is the uncorrelated node mobility of nodes chosen as the next hop. Geographically, a node can be located at point a where it is chosen as next hop, only to move moments later. Introducing mobility awareness reduces path discoveries that occur due to mobility induced link breaks.

Coupling node geographic and mobility information reduces frequency of path discoveries for dynamic environments. Our metrics will help to provide mobility information on choosing the next hop. For example, nodes with high link break volumes will be avoided as successor nodes even when they are geographically located in optimal places. Nodes with high levels of spatial correlation with their neighbors will be preferred as successor nodes using routing metrics under this category.

5.2.5 Routing Metric Performance in Vehicular Ad hoc Networks

Routing among nodes in VANETs is faced with mobility challenges of high speed and changing node density while following road networks for their movements. Relative velocity between two nodes determines the length of validity of a link. Nodes that are moving in the same direction will have lower relative velocity compared to nodes moving in opposite direction moving at the same speed. Our spatial correlation-based routing metrics $sc3$ and $sc4$ are expected to improve the routing performance in VANETs, as they encourage choosing a stable successor in terms of mobility variability with its neighbors and also spatial correlation with the node.

5.2.6 Routing Metric Performance in Delay Tolerant Networks

It may happen that an end-to-end path does not exist between a source and destination node; store-carry-and forward is used to send data to the destination. Finding a suitable node to store and forward data packets for delivery to the destination is the work of the routing protocol. Our time-based metrics are capable of learning node mobility behavior by noting neighbors that tend to spend long duration in the vicinity. Furthermore, the spatial correlation metrics take into consideration stability in terms of groups of nodes, aspect that is essential in delay tolerant networking. We believe that, by sending packets through these reliable neighbors, the packets can be delivered to the destination.

5.3 Future Work

The number of mobile devices and their generated traffic continue to grow. Cisco predicted that traffic from wireless and mobile devices will exceed traffic from wired devices by 2016, and over half of all IP traffic will originate with non-PC devices by 2018 [99]. End users continue to assume new roles of network nodes and also content generators [100][72][28].

These developments pose a number of challenges that need to be addressed:

- Frequent node mobility over spectrum challenged ad-hoc topologies that are created on the fly.
- Further strain on networks in terms of QoS due to the high traffic load and increased node mobility.

Addressing these challenges is future work, and the topics discussed in the subsequent paragraphs are the next steps of work.

UCNs are expected to be more prevalent with the increase in mobile devices as users wish to share data among themselves. With the increase in traffic, prevalence of human mobility and limited spectrum, resultant topologies will have immense challenges to deliver the desired quality of service. The proposed area of work are as follows.

Spectrum and Human Mobility Aware Routing in User-centric Scenarios

Spectrum optimization in the form of cognitive radio wireless networks exist, with *s (CRAHNs)* being specialized of cognitive radio networks for ad-hoc topologies. While spectrum awareness in ad-hoc networks can improve routing, another challenge is the human mobility patterns which the nodes have. A free spectrum slot may only be available for short periods of time due to node mobility triggering route discovery frequently. We propose to work in this area to harmonize spectrum and human mobility pattern constraints to achieve better network performance. By incorporating the human mobility statistical behavior, we believe the routing challenges in UCNs where spectrum is scarce will improve.

QoS and Human Mobility Aware Routing in User-centric Scenarios

In the thesis work, we highlighted the relation between node mobility and QoS. The mobility aware routing metrics were discussed to have a capability to improve QoS in dynamic environments. The metrics are inadequate when QoS issues are a result of other factors such as *Media Access Control, (MAC)* contention. In a quest to address this shortfall, we propose that routing in user-centric scenarios be adaptive to both mobility and QoS issues. The initial work will be to review QoS and node mobility relation further. By making routing metrics adaptive to node mobility and QoS, the increased traffic loads anticipated can be served better.

Mobility Management in Mobile Wireless Networks

Mobile device location determines the cell in which a mobile device will camp in a cellular network. Mobility causes quality degradation as the distance of a mobile device, from the serving base station, increases. A handover is triggered to the best cell. Frequent handovers affect the performance of the network due to continued resource allocation for every handover. On the other hand, the devices on the network are hand-held devices bearing human mobility. Studies of human mobility patterns show preference to some few locations, making short distances and some periodicity and predictability. We believe that, with adequate individual mobility characterization, handovers can be better optimized when human mobility patterns are taken into consideration other than SNR based handovers at layer 2. This can also be applied to load balancing.

Bibliography

Scientific references

[1] A. Aldini and A. Bogliolo, eds., *User - Centric Networking*. No. 978-3-319-05218-2 in Lecture Notes in Social Networks, Springer International Publishing, 2014.

[2] G. Aashima and P. Kumar, "Analysis of different security attacks in manets on protocol stack a-review," *International Journal of Engineering and Advanced Technology (IJEAT)*, vol. 1 Number 5, pp. 269 – 275, 2012.

[3] A. M. Abbas and O. Kure, "Quality of service in mobile ad hoc networks: a survey," *Inteenational Journal Ad Hoc Ubiquitous Comput.*, vol. 6, no. 2, pp. 75–98, 2010.

[4] K. Akunuri, R. Arora, and I. G. Guardiola, "A study of speed aware routing for mobile ad hoc networks," *Int. J. Interdiscip. Telecommun. Netw.*, vol. 3, no. 3, pp. 40–61, 2011.

[5] A. Alighanbari and C. Sarris, "High order s-mrtd time-domain modeling of fading characteristics of wireless channels," in *Antennas and Propagation Society International Symposium 2006, IEEE*, 2006.

[6] F. Bai, N. Sadagopan, and A. Helmy, "The important framework for analyzing the impact of mobility on performance of routing protocols for adhoc networks," *Elsevier Science, Ad hoc Networks Journal-Elsevier Science*, vol. 1, pp. 383–403, 2003.

[7] E. Belding-Royer and C. Perkins, "Evolution and future directions of the ad hoc on-demand distance-vector routing protocol," *Ad Hoc Networks*, vol. 1, pp. 125 – 150, 2003.

[8] M. Benzaid, P. Minet, and K. Al Agha, "Analysis and simulation of fast-olsr," in *Vehicular Technology Conference, 2003. VTC 2003-Spring. The 57th IEEE Semi annual*, vol. 3, pp. 1788 – 1792, april 2003.

[9] M. Benzaid, P. Minet, and K. Al Agha, "Integrating fast mobility in the olsr routing protocol," in *Mobile and Wireless Communications Network, 2002. 4th International Workshop on,IEEE*, 2002.

[10] I. Bhakta, K. Majumdar, A. K. Bhattacharjee, A. Das, D. K. Sanyal, M. Chattopadhyay, and S. Chattopadhyay, "Incorporating qos awareness in routing metrics for wireless mesh networks," in *World Congress on Engineering*, 2010.

[11] C. Boldrini, M. Conti, and A. Passarella, "Impact of social mobility on routing protocols for opportunistic networks," in *World of Wireless, Mobile and Multimedia Networks, 2007. WoWMoM 2007. IEEE International Symposium on a*, 2007.

[12] A. Chaintreau, H. P., J. Crowcroft, C. Diot, R. Gass, and J. Scott, "Impact of human mobility on opportunistic forwarding algorithms," *Mobile Computing, IEEE Transactions on*, vol. 6 no. 6, pp. 606–620, 2007.

[13] N. Chama, A. Junior, W. Junior, P. Mendes, and R. Sofia, *User-centric Networking, Routing Aspects*, ch. chapter I. Springer, 2014.

[14] N. Chama and R. Sofia, "Characterizing multihop routing requirements for node mobility support," in *CRC 2010,Braga,Portugal*, 2010.

[15] N. Chama and R. Sofia, "Redefining link duration: Making routing sensitive to mobility," in *GLOBECOM Workshops (GC Wkshps), 2010 IEEE*, pp. 32 – 37, 2010.

[16] N. Chama, R. Sofia, and S. Sargento, "Multihop mobility metrics based on link stability," in *Advanced Information Networking and Applications Workshops (WAINA), 2013 27th International Conference on*, 2013.

[17] N. Chama and R. C. Sofia, "A discussion on developing multihop routing metrics sensitive to node mobility," *Journal of Communications*, vol. 6, pp. 56–67, 2011.

[18] N. Chama, R. C. Sofia, and S. Sargento, “Node spatial correlation aware routing metrics for user-centric environments,” in *6th International Conference on New Technologies, Mobility and Security, NTMS 2014, Dubai, United Arab Emirates, March 30 - April 2, 2014*, 2014.

[19] N. Chama, R. C. Sofia, and S. Sargento, “Impact of mobility on user-centric routing,” in *Proceedings of the 2011 19th IEEE International Conference on Network Protocols (PhD Forum)*, 2011.

[20] L. Chen and C. Lee, “Neighbor stability routing in manets,” in *In IEEE Wireless Communications and Networking Conference*, 2005.

[21] W. Creixell and K. Sezaki, “Routing protocol for ad hoc mobile networks using mobility prediction,” *Int. J. Ad Hoc Ubiquitous Comput.*, vol. 2, no. 3, pp. 149–156, 2007.

[22] D. Singh, N. Walde, and R. Desai, “Flooding - an efficient routing algorithm,” *International Journal of Advanced Research in Computer and Communication Engineering*, vol. 2, no. 10, 2013.

[23] N. Dang-Quan and P. Minet, “Qos support and olsr routing in a mobile ad hoc network,” in *Networking, International Conference on Systems and International Conference on Mobile Communications and Learning Technologies, 2006. ICN/ICONS/MCL 2006. International Conference on*, 2006.

[24] M. Das, B. K. Panda, and B. Sahu, “Analysis of effect of mobility on performance of aodv in mobile ad hoc network,” in *Computer Communication and Informatics (ICCCI), 2012 International Conference on*, 2012.

[25] F. De Rango, M. Fotino, and S. Marano, “Ee-olsr: Energy efficient olsr routing protocol for mobile ad-hoc networks,” in *Military Communications Conference, 2008. MILCOM 2008. IEEE*, pp. 1–7, 2008.

[26] B. Divecha, A. Abraham, C. Grosan, and S.Sanyal, “Impact of node mobility on manet routing protocols models,” *Journal of Digital Information Management*, 2007.

[27] R. Dube, C. Rais, K.-Y. Wang, and S. Tripathi, “Signal stability-based adaptive routing

(ssa) for ad hoc mobile networks," *Personal Communications, IEEE*, vol. 4, pp. 36 –45, 1997.

[28] P. Frangoudis, G. Polyzos, and V. Kemerlis, "Wireless community networks: an alternative approach for nomadic broadband network access," *Communications Magazine, IEEE*, vol. 49 Number 5, pp. 206–213, 2011.

[29] M. C. Gonzalez, C. A. Hidalgo, and A.-L. Barabasi, "Understanding individual human mobility patterns," *Nature*, vol. 453, no. 7196, pp. 779–782, june 2008.

[30] K. Hrudya, K. Brajesh, and G. Prabhakar, "Impact of mobility on different routing approaches in manets," *International Journal of Computer Applications*, vol. vol 67 number 23, pp. 18–22, April 2013.

[31] X. Hu, J. Wang, and C. Wang., "Stability-enhanced routing for mobile ad hoc networks," in *In Computer Design and Applications (ICCDA)*, 2010.

[32] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum, and L. Viennot, "Optimized link state routing protocol for ad hoc networks," in *Multi Topic Conference, 2001. IEEE INMIC 2001. Technology for the 21st Century. Proceedings. IEEE International*, pp. 62 – 68, 2001.

[33] S. Jamali, B. Safarzadeh, and H. Alimohammadi, "Sqr-aodv: A stable qos-aware reliable on-demand distance vector routing protocol for mobile ad hoc networks," *Scientific Research and Essays*, vol. 6, no. 4, pp. 3015 – 3026, 2011.

[34] N. Javaid, M. Yousaf, A. Ahmad, A. Naveed, and K. Djouani, "Evaluating impact of mobility on wireless routing protocols," in *Wireless Technology and Applications (ISWTA), 2011 IEEE Symposium on*, pp. 84–89, 2011.

[35] D. B. Johnson and D. A. Maltz, *Dynamic source routing in ad hoc wireless networks*, vol. 353. Kluwer Academic Publishers. chapter 5, 1996.

[36] M. Kang, D.Kum, J. Bae, Y. Cho, and A. Le, "Mobility aware hybrid routing protocol for mobile ad hoc network," in *Information Networking (ICOIN), 2012 International Conference on*, pp. 410–414, 2012.

[37] D. Karamshuk, C. Boldrini, M. Conti, and A. Passarella, "Human mobility models for opportunistic networks," *Communications Magazine, IEEE*, vol. 49 Number 12, pp. 157–165, 2011.

[38] S. Karthik, S. Kannan, M. Valarmathi, V. Arunachalam, and T. Ravichandran, "A performance analysis and comparison of multi-hop wireless ad-hoc network routing protocols in manet," *International Journal of Academic Research*, vol. Vol 2 Number 4, 2010.

[39] Y. Khamayseh, O. Darwish, and S. Wedian, "Ma-aodv: Mobility aware routing protocols for mobile ad hoc networks," in *Systems and Networks Communications, 2009. ICSNC '09. Fourth International Conference on*, pp. 25–29, 2009.

[40] Y. Khamayseh, G. Obiedat, and M. B. Yassin, "Mobility and load aware routing protocol for ad hoc networks," *Journal of King Saud University - Computer and Information Sciences*, vol. 23, no. 2, pp. 105 – 113, 2011.

[41] M. Kim and D. Kotz, "Periodic properties of user mobility and access-point popularity," *Personal Ubiquitous Comput.*, vol. 11, no. 6, pp. 465–479, ACM 2007.

[42] S. Kmuar and S. Sharma, "Evaluation of direct and derived mobility metrics of mobility models and its impact on reactive routing protocols," *International Journal of Computer Applications*, vol. 48, pp. 40 – 49, 2012.

[43] L. P. Kong and Q. Yang, "The comparison study of flat routing and hierarchical routing in ad hoc wireless networks," in *Networks, 2006. ICON '06. 14th IEEE International Conference on*, vol. 1, pp. 1 – 6, 2006.

[44] F. Kuhn, R. Wattenhofer, Y. Zhang, and A. Zollinger, "Geometric ad-hoc routing: Of theory and practice," in *Proceedings of the Twenty-second Annual Symposium on Principles of Distributed Computing*, pp. 63–72, 2003.

[45] G. Kumar, Y. Reddyr, and M.Nagendra, "Current research work on routing protocols for manet: A literature survey," *International Journal on Computer Science and Engineering*, vol. Vol. 02, No. 03, pp. 706–713, 2010.

[46] S. Kumar, S. C. Sharma, and B. Suman, "Classification and evaluation of mobility metrics for mobility model movement patterns in mobile ad-hoc networks," *International journal on applications of graph theory in wireless ad hoc networks and sensor networks (GRAPH-HOC)*, vol. 3, pp. 25 –38, 2011.

[47] T. Kumar, R. Muthukumar, and N. Shanthi, "Review of mobility aware clustering scheme in mobile adhoc network," *IJCA Proceedings on International Conference on Research Trends in Computer Technologies 2013*, vol. ICRTCT, pp. 19–24, 2013.

[48] K. Lee, S.Hong, S. Kim, I. Rhee, and S. Chong, "Slaw: A new mobility model for human walks," in *INFOCOM 2009, IEEE , vol., no., pp.855-863*, 2009.

[49] S. Lee, B. Bhattacharjee, and S. Banerjee, "Efficient geographic routing in multihop wireless networks," in *Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing*, pp. 230–241, 2005.

[50] J. Leguay, V. Conan, and T. Friedman, "Qos routing in olsr with several classes of service," in *Pervasive Computing and Communications Workshops, 2006. PerCom Workshops 2006. Fourth Annual IEEE International Conference on*, 2006.

[51] C. Lei and W. B. Heinzelman, "A survey of routing protocols that support qos in mobile ad hoc networks," *Network, IEEE*, vol. 21, no. 6, pp. 30–38, 2007.

[52] Q. Liang and T. Kunz, "Mobility metrics to enable adaptive routing in manet," in *Wireless and Mobile Computing, Networking and Communications, 2006. (WiMob'2006). IEEE International Conference on*, pp. 1 – 8, 2006.

[53] Z. Liang, W. Haohong, and M. Guizani, "How mobility impacts video streaming over multi-hop wireless networks?," *Communications, IEEE Transactions on*, vol. vol 60 number 7, pp. 2017–2028, 2012.

[54] E. Mahdipour, A. Rahmani, and E. Aminian, "Performance evaluation of destination-sequenced distance-vector (dsdv) routing protocol," in *Future Networks, 2009 International Conference on*, 2009.

[55] L. Meng, W. Fu, Z. Xu, J. Zhang, and J. Hua, "A novel ad hoc routing protocol based on mobility prediction," *Inform. Technol. Journal,Asian Network for Scientific Information*, vol. 7, pp. 537–540, 2008.

[56] M. A. Mikki, "Energy efficient location aided routing protocol for wireless manets," *International Journal of Computer Science and Information Security*, vol. 4, no. 1 & 2, 2009.

[57] A. H. Mohsin, K. A. Bakar, A. Adekiigbe, and K. Z. Ghafoor, "A survey of energy-aware routing and mac layer protocols in manets: Trends and challenges," *Network Protocols and Algorithms*, vol. 4, no. 2, pp. 82 – 107, 2012.

[58] M. Musolesi and C. Mascolo, "A community based mobility model for ad hoc network research," in *Proceedings of the 2nd international workshop on Multi-hop ad hoc networks: from theory to reality*, pp. 31–38, 2006.

[59] A. Nguyen, P. Senac, and M. Diaz, "How disorder impacts routing in human-centric disruption tolerant networks," in *The ACM SIGCOMM 2013 Workshop on Future Human-Centric Multimedia Networking (FhMN 2013)*, 2013.

[60] D. Nguyen and P. Minet, "Analysis of mpr selection in the olsr protocol," in *Advanced Information Networking and Applications Workshops, 2007, AINAW '07. 21st International Conference on*, vol. 2, pp. 887–892, 2007.

[61] B. Panda, M. Das, B. Sahu, and R. Das, "Impact of mobility and terrain size on performance of aodv and dsr in mobile ad hoc network," in *Wireless and Optical Communications Networks (WOCN), 2012 Ninth International Conference on*, sept 2012.

[62] K. Pandey and A. Swaroop, "A comprehensive performance analysis of proactive, reactive and hybrid manets routing protocols," *International Journal of Computer Science Issues*, vol. Vol. 8, Issue 6, No 3,, pp. 432–441, 2011.

[63] P. Pasquale and A. Gianluca, "Managing and deploying pervasive wireless internet access through attractive connection sharing and reselling mechanisms," *Journal of Networks*, vol. 8 number 2, pp. 351–364, 2013.

[64] D. Perkins, J. Yang, H. Hughes, and C. Owen, "Reducing the impact of mobility-induced route failures on qos in manets," in *Globecom*, 2004.

[65] D. Rastogi, S. Ganu, Y. Zhang, W. Trappe, and C. Graff, "A comparative study of aodv and olsr on the orbit testbed," in *Milcom*, 2007.

[66] V. Rishiwal, S. Verma, and S. K. Bajpai, "Qos based power aware routing in manets," *International Journal of Computer Theory and Engineering*, vol. 1, no. 1, pp. 47 – 54, 2009.

[67] P. Sambasivam, A. Murthy, and E. Belding-Royer, "Dynamically adaptive multipath routing based on aodv," *In Proceedings Of the 3rd Annual Mediterranean Ad Hoc Networking Workshop*, June 2004.

[68] T. Santhamurthy, "A quantitative study and comparison of aodv, olsr and tora routing protocols in manet," *International Journal of Computer Science Issues*, vol. Vol. 9, Issue 1, No 1, Vol. 9, Issue 1, No 1,, p. 364 369, 2012.

[69] K. Santhiya and N. Arumugam, "Mqarr-aodv: A novel multipath qos aware reliable reverse on-demand distance vector routing protocol for mobile ad-hoc networks," *Journal of Communication Technology*, vol. 3, no. 4, pp. 634– 638, 2012.

[70] B. Shivahare, C. Wahi, and S. Shivhare, "Comparison of proactive and reactive routing protocols in mobile adhoc network using routing protocol property:," *International Journal of Emerging Technology and Advanced Engineering*, vol. Volume 2, Issue 3, 2012.

[71] X. Shu and X. Li, "Relations among mobility metrics in wireless networks," *Int'l J. of Communications, Network and System Sciences*, vol. 1 No 3, pp. 246–253, 2008.

[72] R. Sofia and P. Mendes, "User-provided networks: consumer as provider," *Communications Magazine, IEEE*, vol. 46 number 12, pp. 86–91, 2008.

[73] P. Sondi, D. Gantsou, and S. Lecomte, "Design guidelines for quality of service support in optimized link state routing-based mobile ad hoc networks," *Ad Hoc Netw.*, vol. vol 11 number 1, pp. 298–323, 2013.

[74] C. Song, Z. Qu, N. Blumm, and A. Barabasi, "Limits of predictibility of human mobility," *Science*, vol. 327, pp. 1018–1021, 19th February,2010.

[75] P. Srimanchari, M. Saroja, and M. Venkatachalam, "Effective geographical routing in the presence of unpredictable node mobility," *International Journal of Computer Applications*, vol. vol 23 number 11, pp. 34–40, July 2013.

[76] J. Suyang and J. B. Evans, "Mobility-aware routing protocol for mobile ad-hoc networks," in *Communications Workshops, 2009. ICC Workshops 2009. IEEE International Conference on*, pp. 1 – 6, 2009.

[77] G. Thakur and A. Helmy, "Cobra: A framework for the analysis of realistic mobility models," in *INFOCOM, 2013 Proceedings IEEE*, pp. 3351–3356, 2013.

[78] G. S. Thakur, U. Kumar, W. Hsu, and A. Helmy, "Gauging human mobility characteristics and its impact on mobile routing performance," *International Journal Sensor Networks*, vol. 1 no. 3, pp. 179–191, 2012.

[79] Q. Tran, A. Dadej, and S. Perreau, "Link change and generalized mobility metric for mobile ad-hoc networks," in *IEEE Military Communications Conference (MILCOM 2006)*, pp. 1 – 7, 2006.

[80] C. Tsao, T. Wu, W. Liao, and J. Kuo, "Link duration of the random way point model in mobile ad hoc networks," in *Wireless Communications and Networking Conference, 2006. WCNC 2006. IEEE*, vol. 1, pp. 367–371, April 2006.

[81] J. Tsumochi, K. Masayama, H. Uehara, and M. Yokoyama, "Impact of mobility metric on routing protocols for mobile ad hoe networks," in *Communications, Computers and signal Processing, 2003. PACRIM. 2003 IEEE Pacific Rim Conference on*, vol. 1, pp. 28–30, Aug 2003.

[82] A. Upadhyay and R. Phatak, "Performance evaluation of aodv dsdv and olsr routing protocols with varying ftp connections in manet," *International Journal of Research in Computer and Communication Technology*, vol. 2, no. 8, pp. 531– 535, 2013.

[83] P. Vaidehi and R. Narender, "Comparative study of various qos based routing protocols in mobile adhoc networks," *Int. Journal of Engineering Research and Applications*, vol. 3, pp. 1876 – 1878, 2013.

[84] L. Wenqing, "Path stability based source routing in mobile ad hoc networks," in *Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC)*, pp. 774–778, 2011.

[85] B. Wu, J. Chen, J. Wu, and M. Cardei, "A survey of attacks and countermeasures in mobile ad hoc networks," in *Wireless Network Security* (Y. Xiao, X. Shen, and D.-Z. Du, eds.), Signals and Communication Technology, pp. 103–135, Springer US, 2007.

[86] Y. Wu, W. Liao, C. Tsao, and T. Lin, "Impact of node mobility on link duration in multihop mobile networks," *IEEE Transactions on Vehicular Technology*, vol. 58, pp. 2435 – 2442, June 2009.

[87] H. Xiaoyan, X. Kaixin, and M. Gerla, "Scalable routing protocols for mobile ad hoc networks," *Network, IEEE*, vol. 16 No 4, pp. 11–21, 2002.

[88] Y. Xu and W. Wang, "Meaca: Mobility and energy aware clustering algorithm for constructing stable manets," in *Military Communications Conference, 2006. MILCOM 2006. IEEE*, pp. 1–7, 2006.

[89] M. Yassein, A. Alslaity, and I. Ababneh, "Performance evolutions of velocity-aware routing protocol for mobile ad hoc networks," in *UBICOMM 2012, The Sixth International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies*, 2012.

[90] C. Yawut, B. Paillassa, and R. Dhaou, "On metrics for mobility oriented self adaptive protocols," in *Third International Conference on Wireless and Mobile Communications, ICWMC 07*, 2007.

[91] H. Zafar, D. Harle, I. Andonovic, L. Hasan, and A. Khattak, "Qos-aware multipath routing scheme for mobile ad hoc networks," *International Journal of Communication Networks and Information Security (IJCNIS)*, vol. 4, no. 1, 2012.

[92] J. Zhang, T. Kun, J. Zhao, H. Wu, and Y. Zhang, "A practical snr-guided rate adaptation," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, pp. 2083–2091, 2008.

Non-peer reviewed material

[93] N. Chama, R. C. Sofia, and S. Sargento, "A study on the impact of mobility models in multi-hop routing," Tech. Rep. COPE-SITI-TR-04-15, 2015, COPELABS, University Lusófona, University of Aveiro, 2015.

[94] N. Chama, R. C. Sofia, and S. Sargento, "A discussion on mobility awareness of multi hop routing in user-centric environments," Tech. Rep. COPE-SITI-TR-05-15, Copelabs/University Lusofona,, 2015.

[95] N. Chama, "Impact of mobility on user-centric routing thesis proposal," 2009.

[96] N. Chama, R. Sofia, and S. Sargento, "Impact of mobility on user-centric routing, technical report." http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/339, 2012.

[97] N. Chama, R. Sofia, and S. Sargento, "Impact of mobility on user-centric routing, technical report." http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/245, 2011.

[98] N. Chama, R. Sofia, and S. Sargento, "Impact of mobility on user-centric routing, technical report." http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/127, 2010.

[99] Cisco, "Cisco vni forecast and methodology, 2013 - 2018." http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/, Accessed 26 April 2015.

[100] FON, "Fon." https://corp.fon.com/pt, Accessed on 4 August 2013.

[101] P. Mendes, M. Curado, N. Chama, W. Junior, A. Junior, and V. Rola, "Ucr interim technical report, number siti-tr-12-03,," tech. rep., University Lusofona, 2012.

[102] P. Mendes, W. Moreira, N.Chama, A. Junior, and V. Rolla, "Ucr d3: Routing for user-provided networks," tech. rep., SITILABS / University Lusofona; University of Coimbra, 2013, 2013.

Software and Tools

[103] N. Chama, "Code for a proposal for multihop routing mobility-aware metrics." http://siti.ulusofona.pt/aigaion/index.php/publications/show/295, 2013.

[104] N. Chama, "Mobility-aware metrics for multihop routing, ns module." hthttp://copelabs.ulusofona.pt/scicommons/index.php/publications/show/571, 2013.

[105] CRAWDAD, "http://crawdad.cs.dartmouth.edu/," accessed: 12/12/2013.

[106] gnu.org, "The gnu awk." http://www.gnu.org/software/gawk/manual/gawk.html, Accessed 15 July 2013.

[107] GNUPlot, "Gnuplot tool." http://www.gnuplot.info/, Accessed 21 July 2013.

[108] ORBIT, "http://www.orbit-lab.org/," Accessed:7/12/2013.

[109] R. Roy, "Reference point group mobility," in *Handbook of Mobile Ad Hoc Networks for Mobility Models*, pp. 637–670, Springer US, 2011.

[110] N. Simulator, "Ns 2.34, the network simulator 2.34." http://nsnam.isi.edu/nsnam/index.php, Accessed 10 May 2013.

Standards

[111] H. Badis and K. Agha, "Quality of service for ad hoc optimized link state protocol (qolsr)", ietf manet draft." http://tools.ietf.org/wg/manet/draft-badis-manet-qolsr-05.txt, 2007.

[112] T. Clausen and P. Jacquet, "Optimized link state routing protocol (olsr)." RFC3626, October 2003.

Annex A

This annex provides a list of success indicators, split into contributions to book chapters; publications in peer-reviewed international journals; publications in conference proceedings; posters; technical reports. The full set of indicators correspond to: 1 book chapter; 1 journal paper; 5 papers in conference proceedings (2 in conferences; 2 in workshops; 1 in a symposium); 8 technical reports; 2 software contributions (simulator modules).

Book Chapters

- Namusale Chama, Antonio Oliveira Junior, Waldir Moreira, Paulo Mendes and Rute C. Sofia, User-centric Networking, Routing Aspects, chapter Part I, pp 53-71, Springer, Lecture Notes in Social Networking, volume User-centric Networking: Future Perspectives, 2014. Ed. Aldini & Bogliolo, ISBN 978-3-319-05217-5. DOI: 10.1007/978-3-319-05218-2_3. [13]

Peer-reviewed International Journal Publications

- Chama, N., Sofia, R., "A Discussion on Developing multi-hop Routing Metrics Sensitive to Node Mobility," Journal of Communications, vol. 6, no. 1, pp.56-67, 2011. DOI: 10.4304/jcm.6.1.56-6 [17].
  - http://copelabs.ulusofona.pt/scicommons/index.php/authors/show/10

Publications in Conference Proceedings:

- Chama, N., Sofia, R. , Sargento, S. "Node Spatial Correlation Aware Routing Metrics for User-Centric Environments." In New Technologies, Mobility and Security (NTMS), 2014 6th International Conference on, pp. 1-5. IEEE, 2014. DOI: 10.1109/NTMS.2014.6814037 [18].

- http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/606

- Chama, N.; Sofia, R.C.; Sargento, S., "multi-hop Mobility Metrics based on Link Stability," Advanced Information Networking and Applications Workshops (WAINA), 2013 27th International Conference on , vol., no., pp.809,816, 25-28 March 2013 doi: 10.1109/WAINA.2013.57 [16] .
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/302
- Chama, N., Sofia, C. R., Sargento, "S. Impact of mobility on user-centric routing". In Network Protocols (ICNP), 2011 19th IEEE International Conference on, pp. 286-288. IEEE, 2011. DOI: 10.1109/ICNP.2011.6089063 [19].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/219
- Chama, N.; Sofia, R., "Redefining link duration: Making routing sensitive to mobility," GLOBECOM Workshops (GC Wkshps), 2010 IEEE , vol., no., pp.32,37, 6-10 Dec. 2010. DOI: 10.1109/GLOCOMW.2010.5700336 [15].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/46
- Chama, N.,Sofia, R., "Characterizing multi-hop Routing Requirements for Node Mobility Suport". inProc. CRC 2010, Braga,Portugal, pages 201-203, 2010 [14].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/3

Software

- Chama, N., Sofia, R., Mobility-aware metrics for multi-hop routing, ns2 module. COPE-SITI-SW-13-04, 2013 [104].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/571.
- Chama, N., Sofia, R., multi-hop routing metrics - Link Stability approach, ns2 patch, SITI-SW-12-03,2012 [103].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/295.

Technical Reports

- Chama, N., Sofia, R., Sargento, Susana, A Discussion on Mobility Awareness of Multi Hop Routing in User-Centric Environments, COPELABS, University Lusófona, University of Aveiro, number COPE-SITI-TR-05-15, 2015 [94].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/743.
- Namusale Chama, Rute C. Sofia and Susana Sargento, A Study on the Impact of Mobility Models in Multi-Hop Routing, COPELABS, University Lusófona, University of Aveiro, number COPE-SITI-TR-04-15, 2015 [93].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/742.
- Chama, N., Moreira Junior, W., Junior, A., Curado, M., Mendes, P., "UCR D3: Routing for User-provided Networks", SITILABS / University Lusofona; University of Coimbra, number SITI-TR-13-03, 2013 [102].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/393.
- Chama, N., Sofia, R., Sargento, S., Impact of Mobility on User-centric Routing Progress Report, SITILabs, Universidade Lusófona and Universidade de Aveiro (MAP-TELE), number SITI-TR-12-10, 2012 [96].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/339.
- Mendes, P., Curado, M., Chama, N., Moreira Junior, W., Junior, A, Rola, V., "UCR Interim Technical Report", University Lusofona & University of Coimbra, number SITI-TR-12-03, 2012 [101].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/275.
- Chama, N., Sofia, R., Sargento, S. Mobility Impact on User centric Routing, Progress Report 2010/2011 II, SITI/University Lusófona and University of Aveiro, number SITI-11-05, Technical Report, 2011 [97].

  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/245.

- Sofia, R., Mendes, P., Moreira Junior, W., Ribeiro, Andrea, Queiroz, S., Junior, A., Jamal, T., Chama, N., Carvalho, L. "UPNs: User-provided Networks", Technical Report: Living-examples, challenges, advantages. SITI, University Lusófona, number SITI-TR-11-03, 2011.
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/42.

- Namusale Chama, Rute C. Sofia and Susana Sargento, Mobility Impact on User centric Routing, Progress Report I. SITI, University Lusófona. SITI-TR-11-5/MAP-TELE progress report.2010 [98].
  - http://copelabs.ulusofona.pt/scicommons/index.php/publications/show/127.